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GOLD-QUARTZ VEINS IN METASEDIMENTS OF THE YELLOWKNIFE SUPERGROUP, NORTHWEST TERRITORIES: A FLUID INCLUSION STUDY

by

© PAUL J. ENGLISH

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

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For Kathy

"What is better than gold? Jasper.
What is better than jasper? Wisdom.
And what is better than wisdom? Woman.
And what is better than a good woman? Nothing."

From The Tale of Melibeus, The Canterbury Tales,
Geoffrey Chaucer

ABSTRACT

Samples from twenty gold-quartz vein occurrences in the metasediments of the Yellowknife Supergroup, NWT, were collected and of these nine provided material suitable for fluid inclusion study. The inclusions were studied using petrography, microthermometry, crushing experiments and scanning electron microscopy.

Primary fluid inclusions indicate that the original mineralizing fluid had a salinity of about 5 weight percent NaCl equivalent and homogenization temperatures give a minimum temperature of formation of 250-280^{o}C. Homogenization temperatures from veins within medium grade metasedimentary rocks are slightly but distinctly higher than those for the veins in low grade rocks. The mineralizing fluid was a carbon dioxide-rich sodium chloride brine, with a trace amount of methane.

Published oxygen isotope data give a temperature of formation of 360^{o}C. This difference may be accounted for by a pressure correction for a pressure of approximately 1 kbar (100 MPa). However the existence of 2 primary inclusion populations, one CO_2-rich the other H_2O-rich, indicates that "boiling" (unmixing) may have occurred in which case no pressure correction is required to the homogenization temperatures.

The nature of the gold-transporting agent is not known; the hydrothermal fluid contained both chloride and sulphide components. Published experimental studies on gold geochemistry suggest that a combination of decreasing temperature, decreasing pressure and changing oxygen fugacity caused gold deposition.

Secondary inclusions provide information on a later stage hydrothermal fluid of moderate to high salinity ($\sim$ 10-30 wt. % NaCl equivalent) and probably low temperature (mean temperature of homogenization $\sim 140^{o}C$); minor gold remobilization occurred during this stage. This fluid was NaCl-rich and contained minor amounts of calcium, carbonate and sulphate.

This study suggests that petrography and microthermometry of fluid inclusions and oxygen isotope analysis of quartz are insufficient to distinguish auriferous quartz veins from barren quartz veins.

The data from this study do not conclusively support either a magmatic-hydrothermal or a metamorphogenic origin for the veins. However considering the data along with accounts of gold mineralization elsewhere in the world leads the author to favour genesis of the mineralization in the late stages of metamorphism through metamorphogenic processes.

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Last yet foremost, I would like to thank K. Megli for unending patience and support.

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1. INTRODUCTION

Purpose of Study

The principle aim of this thesis was to carry out a detailed study of the fluid inclusions in quartz of gold veins from metasediments of the Yellowknife Supergroup, near Yellowknife, Northwest Territories. This was done with the objective of determining the composition of the hydrothermal fluid and the environment of deposition, and to evaluate the use of fluid inclusions in exploration for such mineralization.

Background

Much work has been published on the gold veins which occur in metavolcanics at Yellowknife (see Boyle 1979) but little information is available for the gold veins in the metasediments. This, along with published reports of the use of fluid inclusions and oxygen isotopes in prospecting for gold-quartz veins, suggested a detailed fluid inclusion study would be worthwhile.

An initial study of the fluid inclusions was performed by Colin Ramsay, but he studied mainly the barren veins of the area and only included two auriferous veins; also he was unable to obtain salinity data (Ramsay 1973). This study was intended to complement his work.

Methodology

Over twenty gold showings were visited and sampled during the summers of 1976 and 1977. Occurrences in both low grade and

medium grade metamorphic rocks were sampled to determine if there were any significant differences between the two groups. Most of the sample material proved to be unsuitable for study--the samples contained abundant fluid inclusions but these were generally too small to work on. Samples from nine separate gold-quartz veins were found to be suitable.

Samples were studied petrographically and then microthermometric and crushing studies were performed on them. Microthermometry was the major part of the research and was carried out using a Chaixmeca heating/freezing stage. In the last fifteen years fluid inclusion research has undergone a resurgence and three different microthermometric stages are now commercially available; the Chaixmeca stage is perhaps the most versatile of these. Details of the calibration and use of this stage are included elsewhere in this thesis.

To supplement the petrographic studies a few samples were also studied using a scanning electron microscope; this was chiefly to provide details of observed daughter minerals.

Limited oxygen isotope analyses were carried out to provide additional temperature information and to evaluate their use in exploration.

2. GEOLOGY OF THE YELLOWKNIFE DISTRICT

Regional and Local Geology

The study area is within the Slave Province, a part of the Canadian Shield which has remained relatively stable since 2.5 Ga ago. The province is underlain by two main lithologies: Archean granitic and supracrustal rocks (see Figure 1).

The supracrustal succession, which has been named the Yellowknife Supergroup (Henderson 1970) consists of thick sequences of mafic volcanic rocks and turbidites variously deformed and metamorphosed (McGlynn and Henderson 1970). This makes it lithologically similar to the supracrustal rocks of most other Archean cratons but it differs in that sedimentary rocks (~80% by volume) greatly exceed volcanic rocks (~20% by volume) (McGlynn and Henderson 1972).

The volcanic component of the Supergroup in the area around Yellowknife has been well documented (Boyle 1961, Baragar 1966, Henderson and Brown 1966, Padgham 1980a) while Lambert (1977) describes the volcanics that form belts along the Cameron and Beaulieu River systems to the northeast of Yellowknife. The volcanic rocks consist mainly of massive and pillowed basaltic flows with relatively minor intermediate and felsic volcanics, extruded about 2.7 to 2.6 Ga ago (Green and Baadsgaard 1971).

The sedimentary sequence of the Supergroup conformably overlies the volcanics and consists principally of voluminous greywacke and mudstone turbidite deposits with minor amounts of conglomerate and lithic sandstone (Henderson 1972, 1975). The

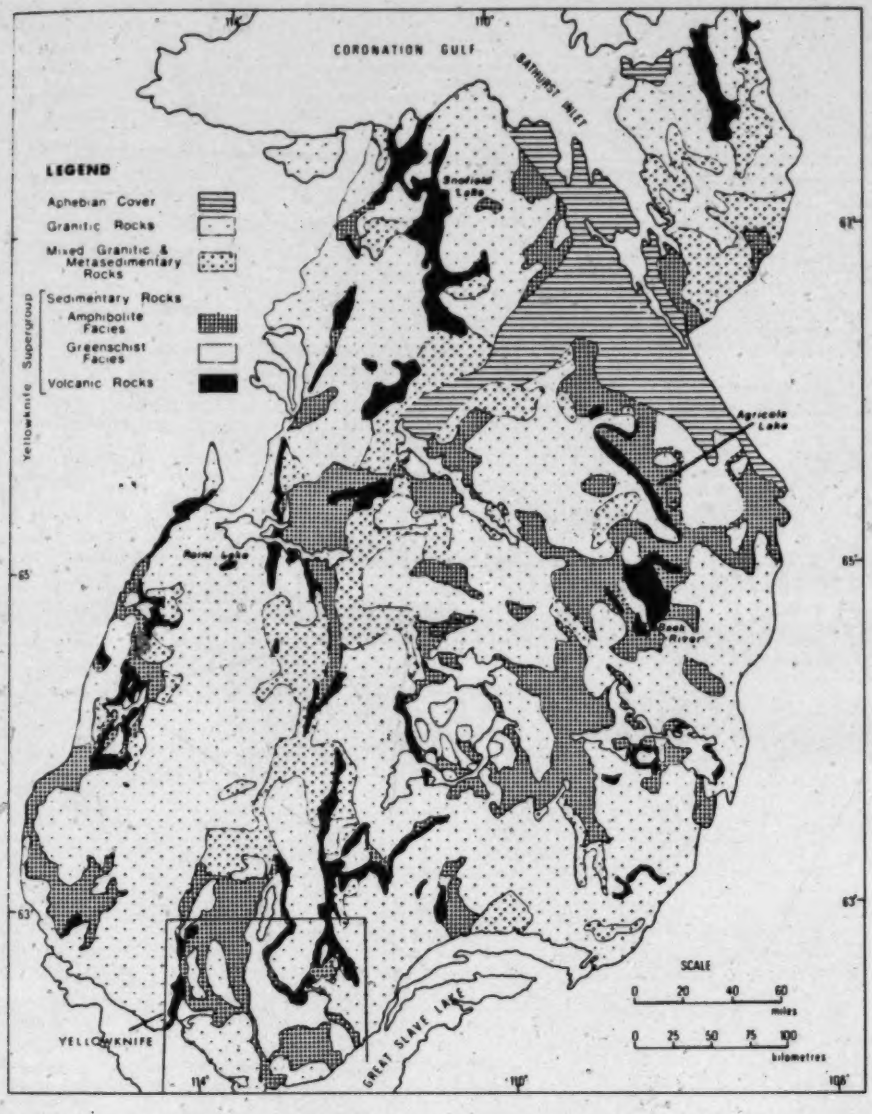


FIGURE 1: Generalized geology of the Slave Province. Area outlined is shown in greater detail in Figure 2. (From Henderson 1977).

Yellowknife-Hearne Lake-Gordon Lake district is a preserved area of supracrustal rocks that has been interpreted as the remnant of a distinct depositional basin separated from other basins by positive areas now represented by areas of granitic rocks (McGlynn and Henderson 1972).

Folinsbee et al. (1968) suggested, by analogy with the Fossa Magna of Japan, that the supracrustal rocks at Yellowknife probably accumulated in about 15 Ma.

The sedimentary rocks are considered to be derived from erosion of an earlier extensive sialic crust.

Granitic rocks underlie about two-thirds of the Slave Province and these can be divided into three categories (McGlynn and Henderson 1972). Firstly, perhaps as much as half of them are gneisses and migmatites that are probably derived from the sedimentary rocks of the Yellowknife Supergroup. Secondly, there is a suite of slightly gneissic rocks that occur as discrete intrusions within the Yellowknife rocks or as large masses between outcrops of the supracrustal strata. These rocks are most commonly granodiorite, quartz diorite and quartz monzonite, and appear to have been mainly emplaced about 2.6 Ga ago (Green and Baadsgaard 1971, Cumming and Tsong 1975).

The third group consists of granitic gneisses and massive plutons very similar to those of the second category but they are distinguished as they are thought to be older than the Yellowknife Supergroup. This is based largely on field geologic evidence (e.g.

Baragar 1966, Davidson 1972, Baragar and McGlynn 1976) and is supported by recent geochronological results. Ages of around 3.0 Ga have been obtained for granitic basement near Indin Lake (Frith, R. et al. 1977) and at Point Lake (R. K. Wanless in Henderson 1977). Also Nikic et al. (1980) have given an age of 3.2 Ga for granitic boulders in a diatreme that intrudes the volcanic rocks at Yellowknife. These boulders are thought to be derived from an underlying sialic basement.

Metamorphism

Although generally referred to by their premetamorphic names the supracrustal rocks were subjected to low pressure regional metamorphism about 2.6 Ga ago (Thompson 1978). Three metamorphic zones have been distinguished: low, medium and high grade (Thompson 1978). These correspond to greenschist, lower amphibolite and upper amphibolite facies respectively. The transition from metagreywacke-slate to knotted schist in the metasedimentary rocks marks the boundary between lower and medium grade, while the transition from knotted schist to gneiss and migmatite marks the boundary between medium and high grade.

Early regional mapping of the province included these three metamorphic zones (e.g. Henderson 1939, 1941a, b, c; Jolliffe 1942, 1946) and they are shown on the compilation of McGlynn (1977). However detailed studies of the metamorphism have only been carried out in limited areas. Ramsay (1973a, b, c, 1974) has documented mineralogical compositions and metamorphic reactions within the

low grade zone in the metagreywackes near Yellowknife. Meanwhile, Kamineni (1973, 1975) has described the metamorphism of the greywackes to the east of Yellowknife in an area within the medium grade zone.

Mineral assemblages within the lower grade pelitic rocks consist of chlorite, white mica, biotite, plagioclase and quartz. Assemblages in pelitic rocks of the medium grade zone include combinations of biotite, muscovite, cordierite, andalusite, plagioclase and quartz. Garnet occurs sporadically in pelitic rocks at any of the three metamorphic grades (Thompson 1978), and gedrite has been documented in the medium grade zone (Kamineni 1975) and there are a few minor occurrences of kyanite in the northeastern part of the province (Frith, R. A. et al. 1977, Percival 1979).

Structural Geology

Numerous structural studies of the Slave Province have been performed (Henderson 1943, Ross 1966, Tremblay 1952, 1976, Ramsay 1973, Fyson 1975, 1978, 1981, Drury 1977). The majority of the structure can be related to a major tectonic event at ~2.6 Ga. Fyson (1975), on the basis of field studies in the Gordon Lake-Ross Lake area and a review of earlier mapping over a larger area, determined a three-phase sequence: two major periods of folding (D_1, D_2) followed by deformation (D_3) related to the intrusion of post-metamorphism plutons.

Greenschist metamorphism prevailed during D_1 and folds resulting from this deformation are isoclinal. Folding during D_2

was also predominantly isoclinal and a prominent north trending schistosity was developed. Evidence for D_3 is mainly the crenulation of this schistosity; during this last period of deformation the metamorphic grade is thought to have been decreasing.

The structural trends in the western half of the province are northerly to northeasterly and these are delineated by the orientation of folds in the metasediments. The folds are similar and normally isoclinal with vertical to steeply dipping axial planes and moderate plunges. Folding is much less apparent in the volcanic sequences (McGlynn and Henderson 1972, Fyson 1975, 1981).

3. GOLD MINERALIZATION IN THE YELLOWKNIFE DISTRICT

Introduction

Gold has been produced from rocks of the Slave Province since the mid-1930's. Production from that time until the present amounts to approximately 11 million ounces which, given the area of the province (~190,000 km^2), is comparable to that from other Archean cratons (cf. Anhaeusser 1976).

Over 240 gold showings and deposits are known within the Slave Province but the bulk of production has come from only 22 of them. The majority of these occurrences are of the quartz lode, or vein, type and most are within 150 km of Yellowknife (Padgham 1980b).

Description of the Mineralization

It has long been recognized that the gold-quartz mineralization can be divided into two main categories based on the host rock lithology (Henderson and Jolliffe 1939). These are: mineralization hosted by volcanic rocks, and mineralization within sedimentary country rocks.

Gold Mineralization in Metavolcanics

It is from the metavolcanic rocks that the bulk of the gold production has come (~85%). They have been studied in great detail including comprehensive research by Boyle (1955, 1959, 1961, 1979). The gold mineralization occurs in auriferous quartz veins and in north-northeasterly trending quartz-carbonate-sericite shear zones

within the metabasalts of the Yellowknife Greenstone Belt. There are two main shear zones: the Campbell shear of the Con mine and the more complex Giant shear of the Giant Yellowknife mine.

The volcanic rocks are extensively altered having variously undergone chloritization, carbonatization, pyritization and sericitization (Boyle 1961, 1979). The chief metallic minerals, occurring with quartz bodies and silicified zones, are pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, galena and a number of sulphosalts and tellurides (Coleman 1953, 1957, Boyle 1961). Theories of genesis of these deposits are reviewed later in this thesis.

Gold Mineralization in Metasediments

The metasediments contain many of the gold showings within the Slave Province, yet these are only responsible for about 4% of the total gold production. The gold occurrences in the metasedimentary rocks have been little studied but their structural control has been noted and Henderson and Jolliffe (1939) classified them into four types which have since been slightly modified (Lord 1951, Boyle 1961, 1979).

These four types are:

1. Quartz veins in contorted schist zones and faults that transect the sedimentary beds.

2. Quartz veins and small stockworks in schist zones and fractures that parallel the sedimentary beds. These comprise quartz veins and stockworks in ruptured and sheared beds and bedding planes, dragged slate beds, contacts and saddle reefs on the noses of folds.

3. Quartz veins and sheeted zones in ruptured and sheared axes of isoclinal folds.

4. Quartz veins and stringer zones in irregular fractures and openings without any continuity or special relationships.

The Ptarmigan and Tom deposits are examples of Type 1. The TA, Joon and Ruth deposits occur in sheared beds and/or bedding planes, as does part of the Camlaren mineralization, and these belong to Type 2. The Camlaren mine also has mineralization concentrated in the nose of a fold, as perhaps does the AM occurrence; these would also be Type 2. The Hidden Lake showing also probably belongs in this type as it appears to occur approximately parallel to bedding. The Tin showing is of uncertain nature. The location of these nine gold-quartz occurrences is shown in Figure 2.

Auriferous veins within the metasediments are typically of limited lateral and vertical extent, generally being narrow and discontinuous and of small potential tonnage. They may be of high grade, from 1-10 oz. of Au per ton, but none of the deposits has produced much gold.

The gold may be spectacular but is always erratic; it is often associated with sulphide minerals, mainly pyrite, sphalerite, galena, chalcopyrite, minor arsenopyrite and pyrrhotite--the association with sphalerite has been noted in particular (Henderson and Jolliffe 1939). Scheelite is recorded from a few of the occurrences, mainly those in the medium grade metamorphic rocks.

Wall rock alteration is very limited and generally on the

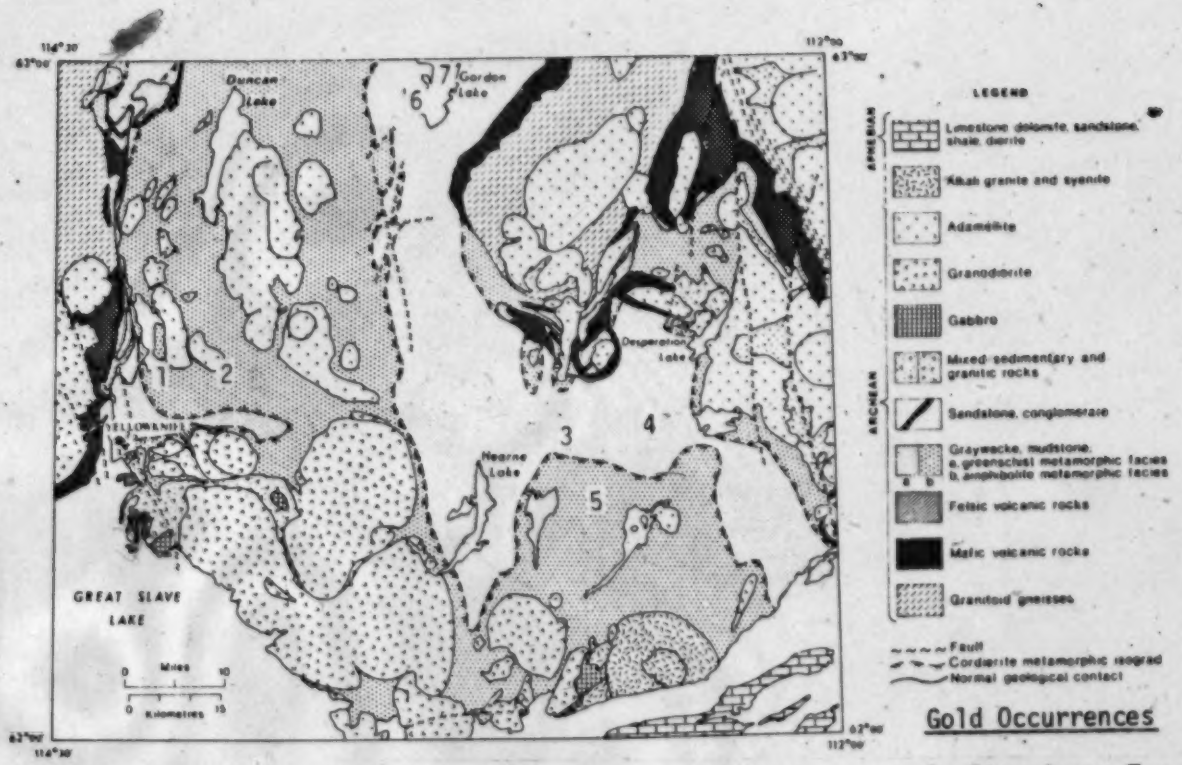


FIGURE 2: Geological sketch map of the Yellowknife-Hearne Lake area, southern Slave Province. (From Henderson 1977).
The locations of the gold occurrences studied are indicated.

Gold Occurrences

1: Ptarmigan, Tom Tin
2: Hidden Lake
3; Joon
4: Ruth
5: TA
6: AM
7: Camlaren

order of a few centimetres. In the low grade metamorphic rocks the alteration zone is often indicated by a thin bleached zone which contains quartz, albite, chlorite, sericite, pyrite, arsenopyrite, occasional pyrrhotite and alteration of biotite. In the medium grade rocks the alteration zone includes quartz, albite-oligoclase, biotite, muscovite, chlorite and some pyrrhotite and arsenopyrite. Tourmaline is common in places, generally associated with biotite (Boyle, 1961). In hand specimens sericite (white mica) and pyrite are notable in alteration zones of veins from the low grade rocks while veins from the high grade rocks often have conspicuous biotite, tourmaline and occasional pyrrhotite in their alteration zones.

About as many gold occurrences are known in the low grade strata as in the medium grade rocks, but it is notable that many of these showings occur not far from the cordierite isograd. Occurrences in the high grade metamorphic rocks are not known.

The showings and deposits that have been studied in this work are described in Appendix I, and their locations are given in Figure 2.

4. FLUID INCLUSION STUDIES

4.1 Principles and Previous Work

Introduction

Fluid inclusions are miniscule samples of liquid and/or gas which were trapped in minerals during their crystallization or recrystallization. In the study of mineral deposits their importance lies in the fact that they may represent remnants of the original mineralizing fluids and can provide information on the nature of the fluid and the environment of deposition.

Using fluid inclusions in geochemical and geothermometric studies involves the following major assumptions (from Roedder 1967):

1. The fluid was trapped as a single homogeneous phase when the inclusion was sealed.
2. The cavity in which the fluid is trapped does not change in volume after sealing.
3. Nothing is added to or lost from the inclusion after sealing.
4. The effects of pressure are insignificant, or known.
5. The origin of the inclusion is known.

Various criteria are applied to ensure these assumptions apply to the suite under study while, in general, numerous experimental studies have vindicated them (e.g. Roedder and Skinner 1968, Roedder and Kopp 1975).

Classification of Inclusions

Fluid inclusions are generally classified into three categories: (i) primary, (ii) secondary and (iii) pseudosecondary. Primary inclusions are those that form at the time of crystallization of the mineral; normally by growth irregularities in the crystal. Secondary inclusions form during the healing of fractures after crystallization has occurred. Pseudosecondary inclusions form during the healing of fractures while crystallization is still going on. Obviously data from secondary inclusions, while they may be of value, do not provide information on the nature of the original ore fluid.

Roedder (1967, 1976, 1981) has provided criteria which can be used to distinguish these three classes of inclusion. However most of them could not be used in this present study; the quartz studied is massive and without growth features. Primary inclusions are considered to be those that are isolated, have a random distribution and show no relation to healed fractures or signs of necking. These criteria are not conclusive but are similar to those used successfully in other studies. Secondary inclusions are easier to identify in that they normally occur in planar arrays which represent healed fractures. Given the nature of the quartz no pseudosecondary inclusions can be recognized.

Composition of the Fluid Inclusions

The composition of the inclusions is studied by petrography and by measurement of the depression of freezing temperatures

(more accurately, melting temperatures) of the aqueous solutions in the inclusions. This depression is an indication of the salt content in the fluid. Fortunately sodium chloride is by far the predominant salt in fluid inclusions (Roedder 1972) and so by reference to the $NaCl-H_2O$ phase system the melting temperatures can be related directly to weight percent NaCl (Roedder 1962, Potter et al. 1978). As this is an approximation assuming no other salt ions in the inclusions the determined values are given as weight percent NaCl equivalent (see Clynne and Potter 1977).

Inclusions which have a concentration of NaCl greater than saturation at room temperature will contain halite crystals. The salinity of these inclusions can be determined in 2 ways: either by estimating the volumes of the components and thence calculating the overall weight percent NaCl, or by measuring the temperature of dissolution of the crystal on heating and comparing with the data of Keevil (1942).

If the data obtained are not consistent with the $NaCl-H_2O$ system (figure 3) reference can be made to other systems through these are not as well documented (see Crawford 1981a).

Homogenization of Inclusions

The homogenization temperature of an inclusion is the temperature at which the components within become one phase, i.e. a homogeneous fluid. Sorby in 1858 proposed that the homogenization temperature gives an indication of the temperature of trapping and it is upon this that fluid inclusion geothermometry is based.

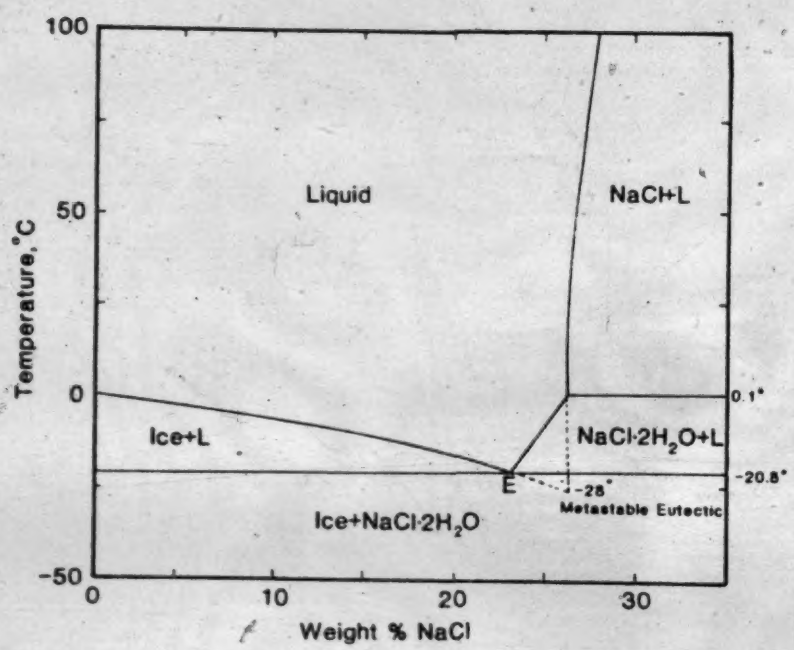


FIGURE 3: The H_2O-NaCl system. (After Potter et al. 1978 and Roedder 1962).

The homogenization temperatures in fact give minimum temperatures of trapping of the original fluids and in most cases it is necessary to calculate a pressure correction before arriving at a temperature of formation. To do this it is necessary to know both the composition of the fluid inclusion, normally in terms of weight percent NaCl equivalent, and the pressure at the time of formation. This latter factor generally has to be determined by independent means. With this information the pressure correction can be determined readily from published graphs (Potter 1977, Lemmlein and Klevtsov 1961).

The pressure is often difficult or impossible to determine and unfortunately the pressure correction (which may amount to hundreds of degrees Celsius) often goes unmentioned in published accounts of inclusion studies.

Previous Studies of Gold Deposits

One of the earliest studies giving inclusion homogenization temperatures is that of Phillips (1868) on gold-quartz veins of California (results of 110-185^{o}C for apparently secondary inclusions) yet relatively few detailed fluid inclusion studies of auriferous quartz veins have been carried out since then. This is no doubt because, as Sawkins et al. (1979) note, they "are notoriously lacking in good material for fluid inclusion studies due to the strong predominance of poorly crystallized quartz containing only very tiny fluid inclusions."

Soviet geologists have performed most of the studies that

do exist and the results are in Russian and often in poorly accessible publications. Some papers are available in translation and more are available as English abstracts (Roedder 1968-1977), but these sources give only a small part of the total information. (About half of all geological literature is in Russian; for fluid inclusion research the proportion is larger, and for inclusion studies on gold-quartz veins still larger, perhaps about 90%.)

For "epithermal" Au-Ag ± base metals veins (subvolcanic and/or "hot spring" Au-Ag deposits) fluid inclusion studies show homogenization temperatures in the range of 200-330°C, with most falling between 250-300°C. Salinities are normally low to moderate and indications of boiling are common (though not a prerequisite for ore formation). For example in their study of the Sunnyside mine, Colorado, Casadevall and Ohmoto (1977) record homogenization temperatures of 270-315°C and salinities averaging 1 weight percent NaCl equivalent for the gold mineralizing stage. While in a study of auriferous quartz-adularia veins in Nevada Nash (1972) observed temperatures of 200-330°C with the gold-bearing stage at 300°C, and salinities of 1-2 weight percent. He estimated formation temperatures of 285-340°C. At the Pueblo Viejo mine, Dominican Republic, homogenization temperatures of 200°C and above, have been noted along with indications of boiling (S. Kesler, personal communication 1980). In a detailed study of the Baguio vein gold deposits, Phillippines, Sawkins et al. (1979) determined homogenization temperatures of 255-285°C for primary inclusions and 205-245°C

for secondary inclusions. The inclusions are mainly liquid-rich and have salinities of 0-5 weight percent NaCl equivalent; signs of boiling were noted along with small amounts of CH_4 and CO_2. A similar range of 240-320°C was observed for homogenization temperatures of the main mineralizing stages of Au-Ag vein deposits in Kamchatka (Andrusenko and Shchepot'yev 1974).

In the genetically related disseminated fine-gold deposits of Nevada, Nash (1972) recorded temperatures around 200°C and salinities averaging 6 weight percent.

The data for gold-quartz low sulfide veins are less detailed but certainly more relevant as the veins are more comparable with those of the Yellowknife district. Koltun (1965--Russian original 1957) in a study of auriferous veins in the Urals recorded temperatures of homogenization of 220-420°C with primary inclusions having a wide range in degree of filling. Three phase inclusions containing liquid CO_2 were noted. In a more recent study of one of the deposits (Kochkar') Anufriyev et al. (1974) have confirmed these results observing homogenization temperatures of 230-450°C chiefly from two phase liquid-vapour inclusions, with a few three phase inclusions containing liquid CO_2. Konovalov (1975) found a similar range of temperatures, 260-460°C, for quartz veins in the Lena gold field. He observed chiefly liquid-rich inclusions which homogenized into the liquid phase; data not being obtainable from most inclusions containing liquid CO_2. The temperature data could be divided into three groups (260-280°C;

260-300°C and 400-460°C) which corresponded approximately with the metamorphic grade in which the veins occurred (i.e. low, medium and high grade respectively). Analysis of the inclusions showed the presence of CO_2 and CH_4. Salinities with a range of 5-10 weight percent NaCl equivalent are given by Bulynnikov et al. (1977) for deposits of the Central Gold-Ore Field (location?) along with homogenization temperatures which mainly fall in the range of 200-300°C. Rather lower temperatures of 110-265°C have been reported from gold-quartz low sulfide veins of the northeast USSR (Davidenko and Chibikov 1978).

Summarizing this and other Soviet work (Roedder 1968-1977, 1972; Shilo et al. 1971) the following generalizations can be made based on the study of primary inclusions in such veins: the hydrothermal solutions were moderate to high temperature (Th 200-400°C) and consisted of low to moderate salinity NaCl solutions rich in CO_2, (with CO_2 content decreasing towards higher grade ore sections) and with CH_4, though a minor component, ubiquitous.

Western studies on veins of this type are few but the following provide some information. Rye and Rye (1974) in a detailed study of the Homestake mine, South Dakota, observed two main types of inclusion: two phase inclusions consisting of liquid H_2O and a CO_2-rich vapour, and three phase inclusions of liquid H_2O, liquid CO_2 and CO_2-rich vapour. They considered most of these inclusions to be secondary and recorded small amounts of CH_4 in all analyzed samples; no homogenization data are given. In a study of

the conglomerates of the Witwatersrand basin, Shepherd (1977) notes that pebbles of vein quartz with a low proportion of inclusions containing liquid CO_2 are associated with gold, while those which show a relatively high proportion of inclusions with liquid CO_2 are associated with the uranium mineralization. Homogenization temperatures in the range of 200-400°C are given. Krupka et al. (1977) suggested inclusion homogenization temperatures of 210°-380°C and low to moderate salinities for the mineralizing stage of the O'Brien mine, Quebec, based on observation of two phase inclusions with widely varying degrees of filling (taken as an indication of boiling). For the Dome mine, Ontario, Kerrich and Fryer (1979) recorded homogenization temperatures of 330-370°C for primary inclusions in quartz veins. In the Yellowknife district itself, Chary (1971) observed homogenization temperatures of 270°C (only four measurements) for the Con mine and CH_4 has been detected in quartz from this mine (W. Bale, personal communication 1977). Ramsay (1973) determined temperatures of 150-310°C for primary inclusions and 100-200°C for secondary inclusions in quartz of two veins within the metasediments (the Tom and Ptarmigan occurrences).

As one would expect these results compare quite well with those from the Soviet literature, and this survey shows the predominant role of medium temperature, low to moderate salinity fluids in the formation of auriferous quartz veins.

4.2 Types of Inclusions

As well as being classified into primary, pseudosecondary or secondary, inclusions can be grouped based on their appearance and composition as determined microscopically. Division is essentially on the basis of the components and their phases observed, along with additional information from crushing experiments. The inclusions observed in this study have been categorized into three main types which are described below and illustrated in Figure 4 .

Type I. Liquid-rich. These inclusions are by far the most numerous type observed. They vary from equant to irregular and range in size from <1 to approximately 20 μm. Many are in the 5-10 μm diameter size range but most are 1 μm or less. Various subtypes can be recognized:

a) Liquid-rich (5-15% vapour by volume) secondary inclusions. Generally simple two-phase inclusions though some contain a small halite daughter mineral (1-5% by volume). Most of the inclusions observed are of this type.

b) Liquid-rich (10-30% vapour) primary inclusions. Generally two-phase with the vapour often being CO_2-rich. A three-phase variety is observed in many samples; these contain liquid CO_2, perhaps up to 20% by volume. The distinction between these two varieties is gradational--an inclusion may contain as much as 10% liquid CO_2 before it can be observed as a separate phase (Roedder 1972). Some of these inclusions contain traces of CH_4, presumably dissolved

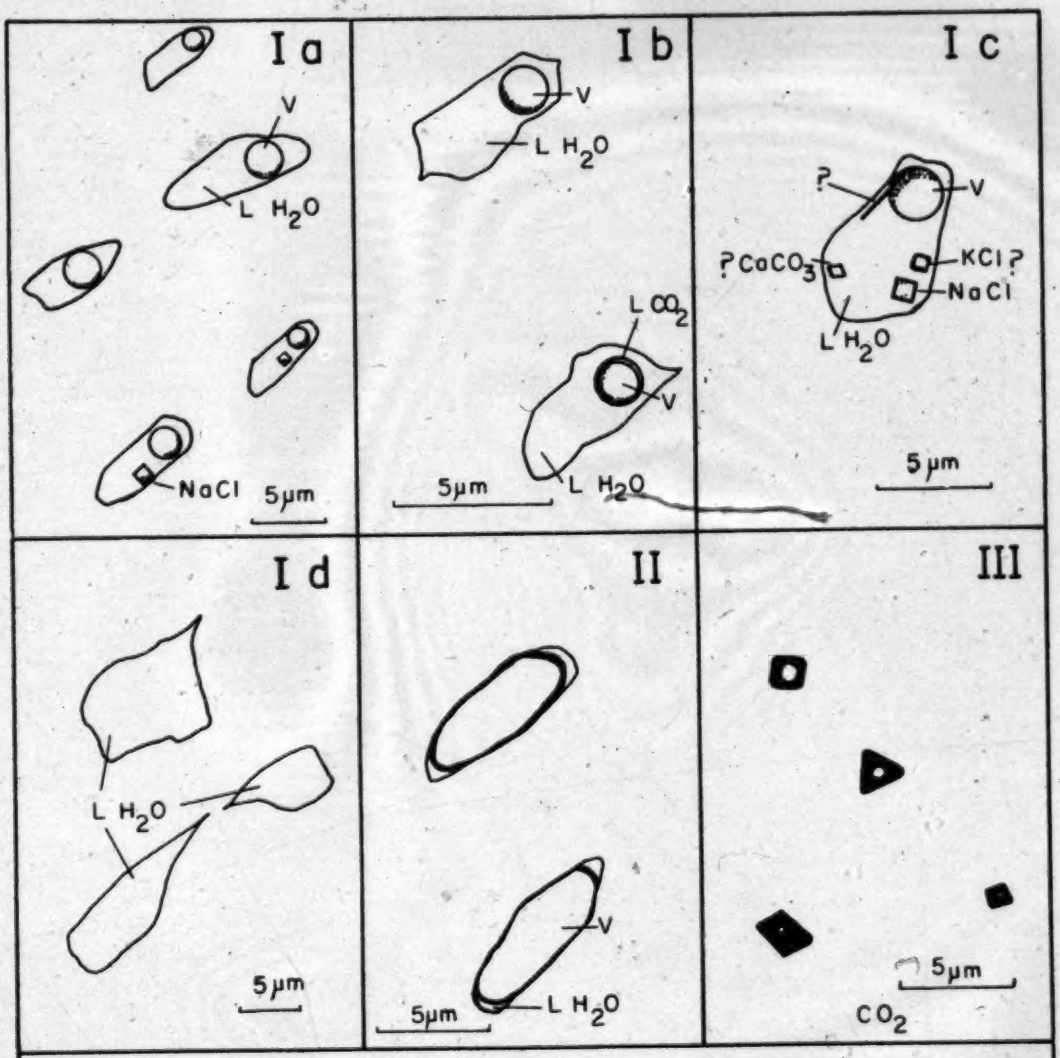


FIGURE 4: Fluid inclusion types observed in quartz of the auriferous veins. See text for explanation.

in the CO_2 phase.

c) Multiphase inclusions, mainly secondary, though some may be primary. These inclusions, few in number, may contain daughter minerals of halite, another cubic crystal (possibly sylvite), a small anisotropic crystal (possibly calcite) and a thin needle-like crystal (see SEM section).

d) Liquid-filled inclusions, representing very low temperature late stage secondaries.

Type II. Vapour-rich. These generally equant inclusions are much less common than Type I but were noted in most samples; they are mainly primary but some are secondary. The vapour content varies from virtually 100% ("empty" inclusions) to about 95%. No daughter minerals noted. Vapour is CO_2-rich with possible traces of CH_4. (Distinction between liquid-rich and vapour-rich inclusions is of course arbitrary with a division at 50%. However very few inclusions of definite origin were noted in the 30-90% vapour range.)

Type III. CO_2-bearing. Very small inclusions, many having a negative crystal shape, which could not be seen into. Majority appear to be primary. Crushing shows that some contain CO_2 under high pressure. These may simply be a variety of Type II, or they could grade into the CO_2-bearing inclusions of Type Ib. Some of these inclusions contain an unidentified noncondensable gas (perhaps nitrogen?).

4.3 Microthermometric Results

The gold-quartz veins provided much material which was unsuitable for fluid inclusion studies but some sixty samples from

nine gold occurrences were usable. The small size of the inclusions made microthermometric measurements difficult and limited the amount of information that could be collected.

Low Temperature Studies

Salinity determinations were carried out on over two hundred inclusions, more than a third of which were classified as primary. These measurements were made by observing the melting temperature of the frozen aqueous phase in the inclusions. All the determinations were on liquid-rich inclusions of Types Ia and Ib.

Hydrohalite, $NaCl \cdot 2H_2O$, which is formed in saturated or near saturated brine at low temperatures, was tentatively identified in a few secondary inclusions which at room temperature contained a halite crystal.

Carbon dioxide hydrate, with an ideal formula of $CO_2 \cdot 5.75H_2O$, would be expected to form in CO_2-rich inclusions at low temperatures. The melting temperature of this clathrate is dependent on the vapour pressure of CO_2 within the inclusion (and less importantly on the CH_4 content) and commonly ranges between about $+5^oC$ and -5^oC, though it can exist up to $+10^oC$ (Kelly and Turneaure 1970, Hollister and Burrus 1976). Given the CO_2 content indicated by crushing studies, this compound was searched for but was not found. It is, however, not easy to identify under the best of conditions, being isotropic and having a refractive index very similar to that for water. The results of the salinity determinations

are tabulated in Appendix III and displayed in Figure 5.

Primary inclusions have a range in salinities from 1 to 18 weight percent NaCl equivalent; most values fall in the range of 3-6 weight percent and the mean value is about 5.5 weight percent. There is no significant difference between the salinities of inclusions from veins within low grade metamorphic rocks and those determined for veins from medium grade rocks.

Secondary inclusions show a range in salinities from 6 to 22 weight percent NaCl equivalent; most values are in the 8-12 weight percent range and the mean is about 11 weight percent with a small subsidiary group of values at 18-19 weight percent. Again determinations from veins in low grade host rocks are comparable with those in medium grade rocks. The average salinity for the secondary inclusions is in fact higher than that given above, for a significant number of secondaries contain halite. From a few measurements of dissolution temperature of these crystals salinities are estimated to be in the 29-31 weight percent range (Keevil 1942). This corresponds well with estimates made using approximate volume calculations.

In summary, the data suggest an original mineralizing fluid of low salinity and a later hydrothermal stage with a fluid of moderate salinity, with the possibility of another late stage fluid which at room temperature varies from over-saturated to just under-saturated. (The age relationship of this high salinity fluid to the moderately saline fluid is unknown.)

The temperature measurements in this salinity study, along

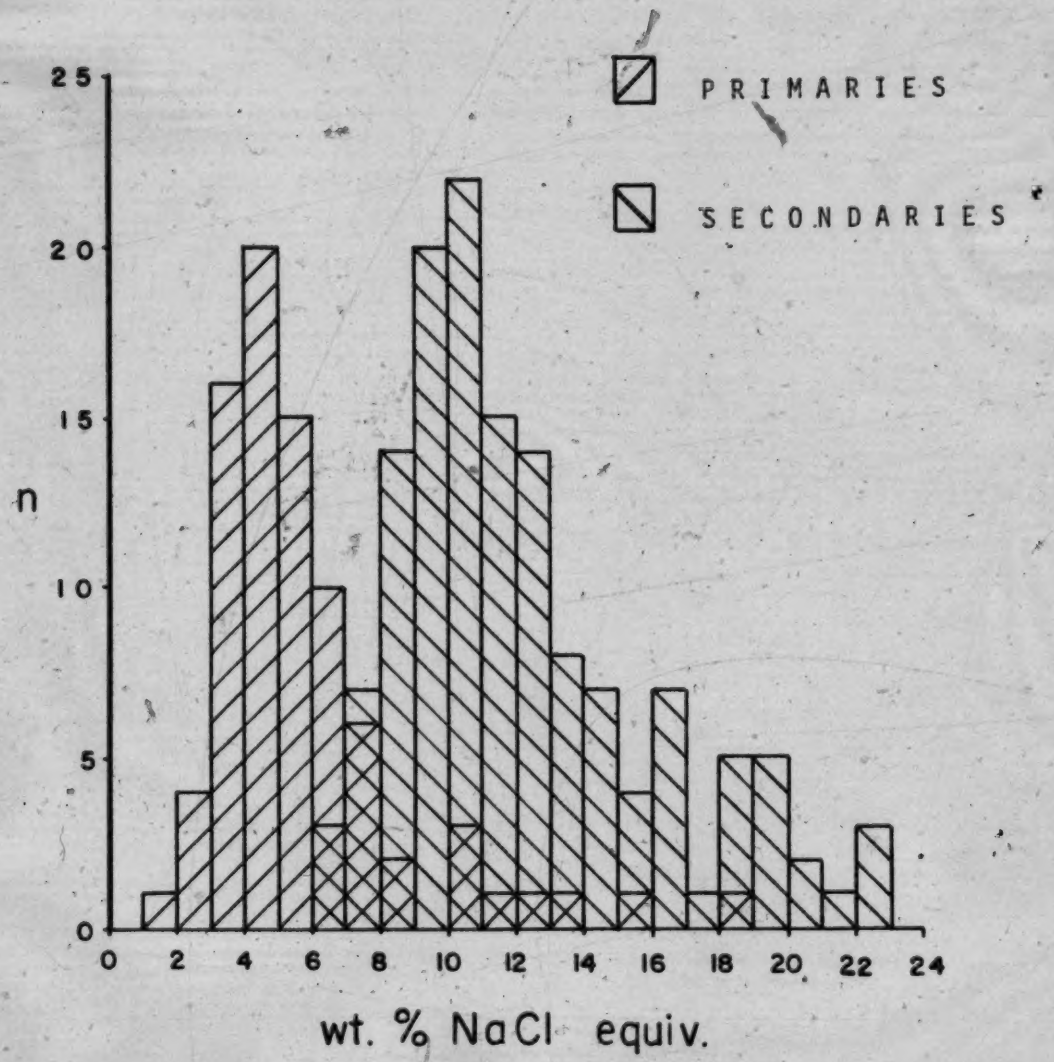


FIGURE 5: Salinity results for primary and secondary inclusions. Determined from Tm ice.

with observation of first melting temperatures between -28°C and -20°C, are consistent with the fluid being a brine containing predominantly sodium and chlorine.

High Temperature Studies

Determinations of homogenization temperatures were performed on nearly five hundred inclusions in the over sixty samples. Over one-third of the inclusions were primary.

Numerous duplicate measurements of homogenization temperatures of particular inclusions were made and these showed good consistency but such measurements were not possible on most of the inclusions. The vapour phase did not always reappear on cooling and some inclusions decrepitated just after homogenization. A number of inclusions of Type Ib and CO_2-bearing inclusions of Types Ib and III decrepitated before homogenization. This is due to the high internal pressure developed and is a common phenomenon of CO_2-H_2O inclusions (Roedder and Bodnar 1980, Burruss 1981).

Nearly all of the determinations were made on Type I inclusions and these homogenized in the liquid phase. Only 10 measurements of temperature of homogenization (Th) were obtained for Type II inclusions; these homogenized in the vapour phase.

The results are tabulated in Appendix IV and shown in Figures 6 and 7.

Primary inclusions have a range in Th of 200-330°C with a mean of 260°C. Figure 7 shows how the data can be divided into two distinct groups based on whether the samples were from veins

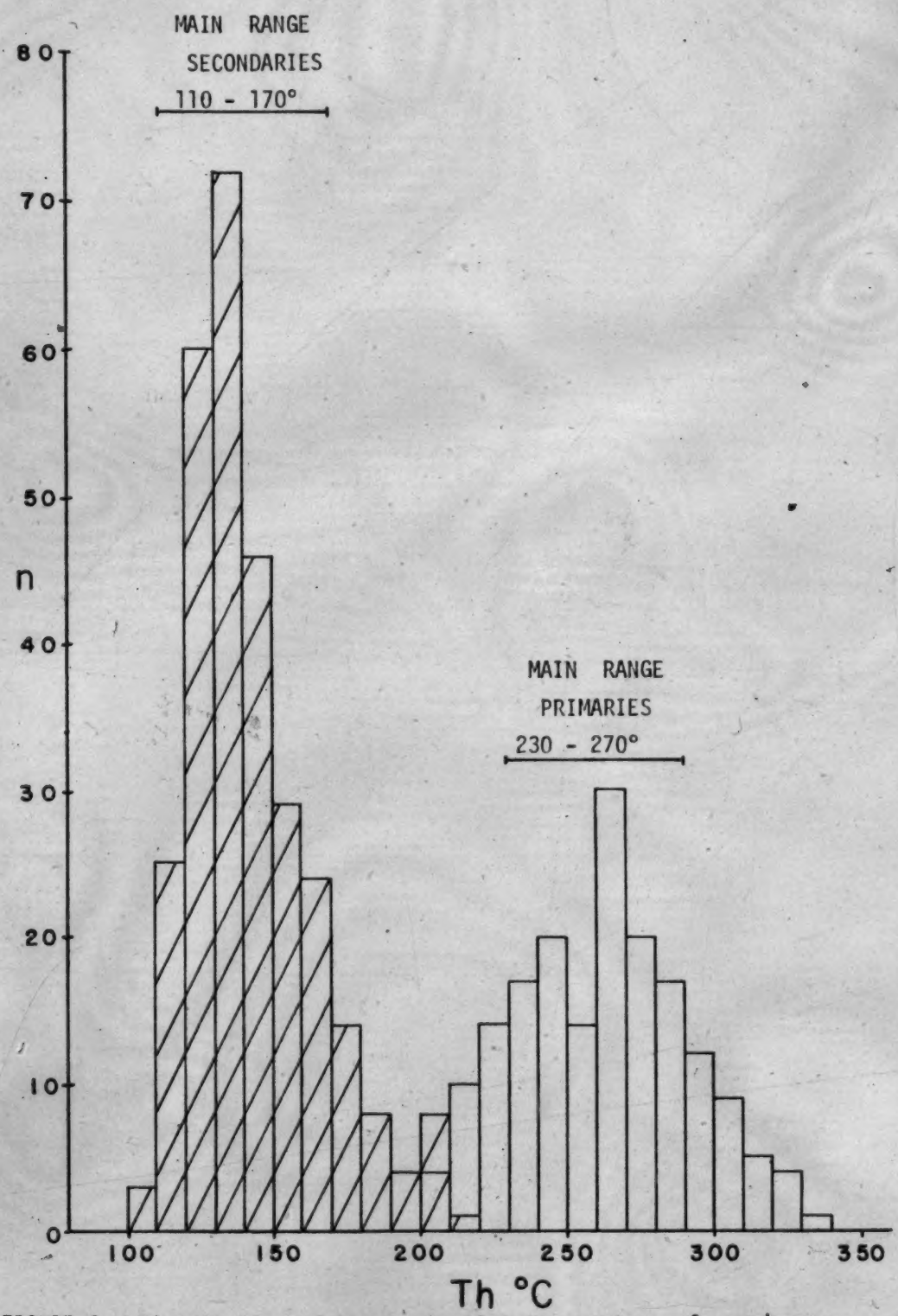


FIGURE 6: Distribution of homogenization temperatures for primary and secondary inclusions.

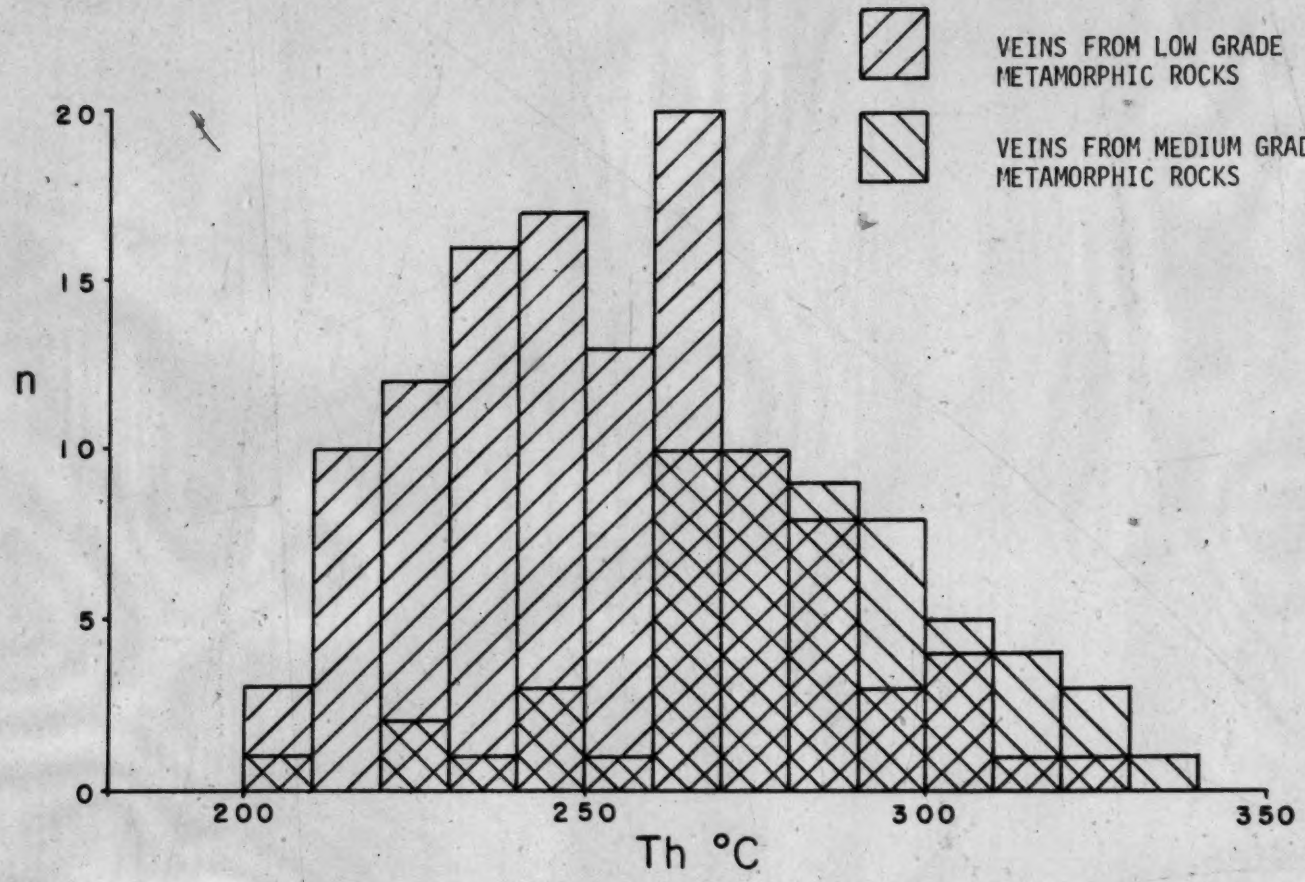


FIGURE 7: Distribution of homogenization temperatures for primary inclusions; veins from low grade and from medium grade metasediments.

in low grade metamorphic rocks or from veins in medium grade rocks. The ranges of the two groups are virtually identical (200-320°C and 200-330°C) but inclusions from quartz of veins hosted by low grade rocks give values with a mean of 250°C and a main range of 210-270°C while values obtained on veins from higher grade rocks have a mean of 280°C and a main range of 260-310°C (cf. Konovalov 1975).

The ten values of Th obtained on vapour phase inclusions ranged from 280-322°C with a mean of 295°C.

Secondary inclusions have a range in Th of 100-220°C with a mean value of about 140°C; most results fall in the range of 120-150°C. There is no difference in Th of inclusions from veins within different metamorphic grade rocks.

The lack of overlap in Th for primary and secondary inclusions could be real although it is possibly due to observer bias whereby inclusions which would have fallen in this range were assigned an uncertain origin (i.e. not definitely primary nor definitely secondary) and went undetermined.

The occurrence of two sets of inclusions (Types I and II primaries), one with liquid predominant and the other vapour-rich and the lack of intergradation between the two suggest "boiling" of the original hydrothermal fluid (more accurately an indication of H_2O-CO_2 immiscibility) (Roedder 1967). The determinations of Th on vapour-dominated inclusions do not contradict this but the small number of values can hardly be considered sufficient to

substantiate this proposition. It cannot be proved that the two types of inclusion are coeval.

However given these reservations, if boiling did take place then no pressure correction is necessary for the primary inclusion data--the homogenization temperatures are equivalent to formation temperatures (Roedder and Bodnar 1980). For the secondary inclusions no estimate of pressure can be made and so the values of Th represent minimum temperatures for the later stage fluid. As an example of the corrections that might be necessary, pressures of 0.5, 1, and 2 kbar on a 10 weight percent NaCl solution would give corrected values for the 140°C mean value of 190°, 230° and 305°C respectively (Potter 1977).

4.4 SEM Study

To provide further information on the composition of the fluid inclusions quartz samples from six of the gold vein occurrences were studied using a scanning electron microscope (SEM). The aims were to confirm the composition of the brine if possible and to identify any daughter minerals observed. The method used was very similar to that described by Metzger et al. (1977).

A Cambridge S150 SEM fitted with a Kevex energy dispersive analyzer (EDA) was used. Images of the daughter minerals were obtained using the SEM with a scanning electron beam and qualitative analyses were achieved with the beam stationary. An accelerating voltage of 15 kV was used with the electron beam being

~0.25 μm in diameter. Analyses were performed with count rates of 1400-2000 counts per second.

The samples used were fractured fragments of quartz taken, where possible, from specimens which had yielded fluid inclusion samples with multiphase inclusions. Further details of the procedure followed are given in Metzger et al. (1977).

Results

Excellent images of inclusions were obtained (Plates I and II). Most inclusions appeared empty but in a number of cases the inclusions contained or were surrounded by what was apparently a 'decrepitate' (an evaporite from the brine enclosed inclusions, formed on their opening). Using the EDA, all the qualitative analyses determined Na and Cl in the decrepitate, while in a few cases relatively low amounts of K were also detected; no other elements were noted.

As for the daughter minerals no distinct halite cubes were noted; frequently observed in petrographic studies, these crystals were presumably lost on opening of the inclusions. However other daughter minerals were tentatively identified. These were calcite, gypsum, sylvite and a platy K-Al mineral, perhaps a mica or clay mineral. These identifications were based both on the qualitative analyses and the crystal morphology. The analyzer can not detect carbon and neither could sulphur or silicon be determined in the daughter minerals. The samples are coated with gold (so

PLATE I

a) An inclusion containing NaCl decrepitate on the left and on the right two apparently platy K, Al (Si) minerals. Presumably micas or clays. Ruth.

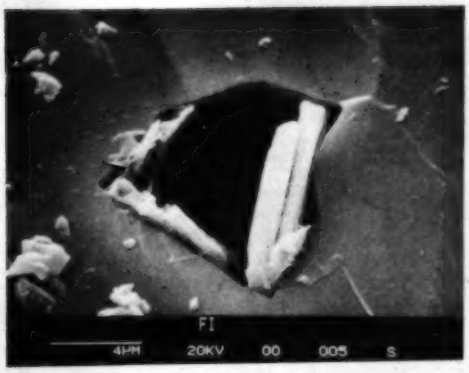
b) An irregularly shaped inclusion containing two Ca-rich minerals. The larger one is probably gypsum (cf. Nesbitt and Kelly, 1977, figure 12), the other may be calcite. Camlaren.

c) A small inclusion, tending towards a negative crystal, with several daughter crystals: a needle-like crystal, Ca-rich perhaps gypsum, and two Cl-rich minerals in the upper left of the inclusion (poorly visible). The larger one contains K and is probably sylvite, the other is unidentified. Note NaCl decrepitate around the inclusion. Joon.

d) Irregular inclusion containing an arrowhead shaped daughter mineral with a strong Ca spectrum. Crystal is twinned and is probably gypsum. AM.

Note bar scale on all images.

PLATE I



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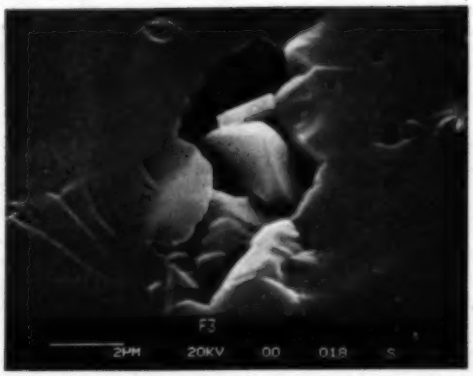


b

c

d

PLATE II

Note bar scale on all images.

a) Empty inclusions on a fracture surface of quartz. All of the inclusions are secondary as indicated by the linear arrays. Camlaren.

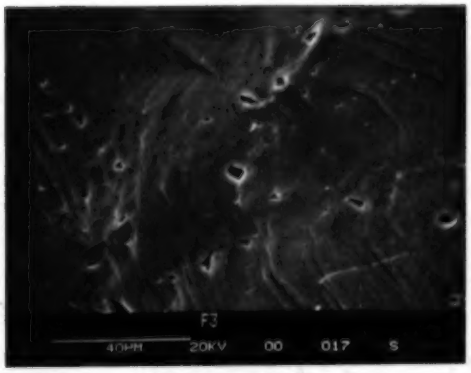
b) A relatively large inclusion showing signs of necking down. The indicated material, along with most of that in and around the inclusion is NaCl decrepitate. The particle to the lower left of the arrowed NaCl is a fragment of quartz. Hidden Lake.

c) A very small inclusion, ringed by NaCl decrepitate, showing negative crystal shape. The particle in the left centre is a quartz fragment. Within the inclusion are, in the upper left, a Cl-rich daughter mineral (identity unknown) and in the lower centre, halite--apparently decrepitate rather than a daughter mineral. Hidden Lake.

d) A filigree of NaCl, a habit which was suprising but not uncommon in the samples observed. It is presumably a decrepitate. Ruth.

e) A relatively large irregular inclusion containing a Ca-rich rhombohedral daughter mineral, undoubtedly calcite.

PLATE II



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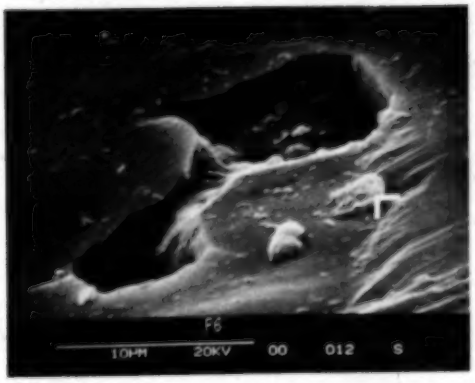

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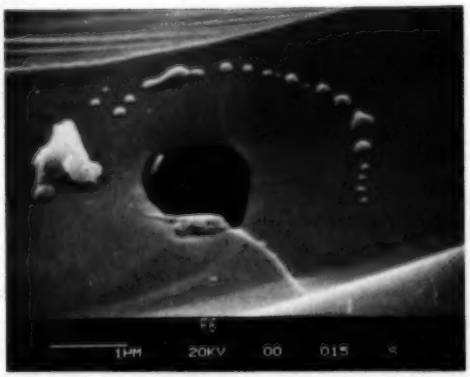

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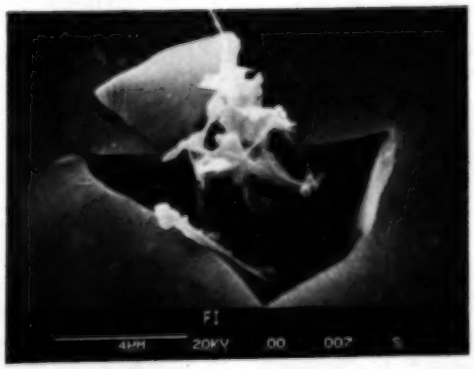

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e

they are electrically conductive) and the X-ray spectrum for gold overlaps and conceals that of sulphur. The X-ray spectrum for silicon from the host quartz swamps what silicon spectrum might be obtained from the daughter minerals.

The mineral dawsonite, $NaAl(CO_3)(OH)_2$, reported from gold-quartz veins of California and elsewhere (Coveney and Kelly 1971) was not observed either petrographically or using the SEM.

4.5 Fluid Inclusions and Mineral Exploration

Fluid inclusion research has provided much information on the nature of mineralizing fluids and on the conditions of ore genesis. However in recent years in particular there have been several attempts to make more practical use of fluid inclusions; notably in their application to mineral exploration (Roedder 1977). Nash (1976) clearly shows that the presence of halite-bearing inclusions, especially coexisting with gas-rich inclusions, is a favorable sign in the exploration for porphyry copper deposits. Similarly Kostina and Sushchevskaya (1975) demonstrate how analysis of aqueous extracts from inclusions in quartz of felsic volcanic rocks may provide an indication of massive sulphide ore. Considering that a vast multitude of methods have been applied, or at least attempted, in the prospecting and evaluation of gold deposits (see e.g. Boyle 1979, pp. 446-488) it is not surprising that fluid inclusions have not been ignored in this regard. A brief review of the available information follows.

There have been numerous qualitative observations of the

abundance and nature of fluid inclusions in quartz of vein-type gold mineralization, and comparisons to the barren quartz veins within the same area. Courtis (1890) studied samples from numerous gold mines in California and compar (quartz from barren parts of the vein systems) with 'good quartz' (quartz associated with ore). He noted that gold-bearing quartz had a relative abundance of fluid inclusions many of which contained liquid carbon dioxide. His description of the inclusions as being arranged in 'parallel lines or rows' suggests that they may be of secondary or pseudosecondary origin, yet their association with the gold indicates an apparent connection between CO_2-rich fluids and the deposition (or redeposition) of the gold.

Lindgren (1896, p. 130) in a study of the gold-quartz veins of the Nevada City and Grass Valley districts, California, recorded that fluid inclusions are extremely abundant, noting they are small, irregular in shape and sometimes contain rapidly moving bubbles. Heating to above $30^{o}C$ indicated the absence of liquid carbon dioxide. He stated there was no recognizable relationship between the fluid inclusions and the richness of the quartz.

Cairnes (1937, p. 53) in a study of gold-quartz veins of the Pioneer-Bralorne area, British Columbia, noted that:

> "There was perhaps a suggestion that these inclusions were more abundant and active bubbles more conspicuous in specimens of higher grade gold-quartz but not enough slides were examined to prove or disprove this point."

In a decrepitation study of auriferous quartz veins at the

O'Brien Mine, northwestern Quebec, Blais (1954) found that auriferous quartz decrepitated in the temperature range 75-120°C whereas barren quartz decrepitated above 130°C. A similar study of the Con Mine at Yellowknife by Boyle (1954) determined that the details of any relationship between decrepitation temperatures and gold-bearing quartz are very complex and not consistent, though his results showed there was a tendency for ore quartz to have higher decrepitation temperatures than the barren quartz.

Davidenko and Valpeter (1969) in a study of veins in Western Chukotka, USSR, noted that primary inclusions in gold-bearing veins were multiphase whereas the barren veins were simple gas-liquid inclusions.

Boyer et al. (1967) recorded CO_2-rich inclusions in auriferous quartz from Salsigne, France, and their absence in barren quartz. They noted that such an association is not peculiar to the Salsigne gold mine and gave other examples from gold occurrences in French Guiana, Surinam and Italy, among others. Similarly, Machairas (1970) commented on the association of CO_2-rich inclusions and auriferous quartz. He stated that for gold-bearing quartz, gold content increases as CO_2 content increases, and to substantiate this, presented analyses of samples from auriferous districts in France, French Guiana and Canada.

Vertushkov (1966) determined the "moisture/gas ratio" (essentially the ratio of H_2O to CO_2) in some 150 samples of vein quartz from the southern and central Urals. He shows that the

value of this ratio decreases with metamorphic grade and that the ratio from quartz of gold veins is lower than for quartz of barren veins from the same locality. This study is expanded in Vertushkov et al. (1970) in which the molar ratio $H_2O:CO_2$ in 2500 samples of quartz from various Ural deposits was determined. Vertushkov and coworkers show that this ratio is notably lower for gold-bearing quartz than for barren quartz. For example the following results were obtained from the Byn'gi deposit:

VH_2O/VCO_2	Au content, ppm
8.7	0.6 "barren quartz"
6.0	3.5
2.5	9.2 "ore quartz"

Ryabova (1973) in a study of mineralization in Dagestan, USSR, showed that ore-bearing quartz contains more inclusions per volume of sample than barren quartz. This was indicated by both decrepitation intensity and loss on ignition results. Also the ore-bearing quartz gave decrepitation temperatures of 240-280°C while the barren quartz gave values of 180-210°C.

Korobeynikov and Matsyushevskiy (1973) also noted increased decrepitation approaching and within ore-bearing zones; it being possible to correlate gold concentration and intensity of decrepitation in many auriferous deposits of Siberia and the far eastern USSR.

Summarizing these notes it can be said that, when compared to barren quartz, auriferous quartz may show a greater abundance of

inclusions, a significant but higher content of CO_2--perhaps best expressed as the ratio of H_2O to CO_2 in the primary inclusions--and generally higher decrepitation temperatures and intensities. Obviously the decrepitation observations are not consistent throughout the various studies and it is likely that the varying nature of the quartz is more significant than the varying gold content.

It is difficult to apply these observations to the veins in the metasediments of the Yellowknife district. Variation in abundance of inclusions is as large within a single vein as it is between auriferous and barren veins. Ramsay (1973) indicates the common occurrence of CO_2 in both the gold-bearing veins and the irregular barren veins. Qualitative observations of Ramsay and of this study have not determined any significant difference in CO_2 content between the two vein types. Also Ramsay finds no significant difference in the homogenization temperatures of inclusions in the auriferous and the barren veins. Results of this research do not alter his observation.

It is apparent that petrographic and microthermometric observations cannot be used to distinguish barren veins from ore-bearing veins in the Yellowknife district, but that there remains the potential to draw a distinction on the basis of an analytical method such as that of Vertushkov (1966).

5. OXYGEN ISOTOPE STUDY

Introduction

Fluid inclusion observations provide an indication of the temperature of formation of the quartz veins and give data on the composition of the hydrothermal fluids responsible for their formation. Preliminary oxygen isotope analyses were performed to augment this information, with the aim of evaluating the use of the method in mineral exploration and, in combination with published data, of determining the ultimate source of the fluids.

Background and Methodology

Water is the main component of hydrothermal fluids and a knowledge of its origin is basic to any hypothesis on the genesis of a mineral deposit. Natural waters of various origins show systematic variations in their ^{18}O contents due to isotopic fractionation during natural chemical and physical processes. Consequently oxygen isotope analysis is an ideal method to characterize ore-forming fluids as it provides information on the nature of the water molecules themselves.

Five major types of water have been distinguished on the basis of isotopic analyses and all may be active in the formation of mineral deposits. The five types are: meteoric water, ocean water, connate water, metamorphic water and primary magmatic water (Taylor 1979). The isotopic character of these waters may be modified and more than one type may be involved in the formation of a

particular deposit (White 1974).

The oxygen isotope ratios of quartz were measured using the BrF_5 method (Clayton and Mayeda 1963). Quartz was treated with BrF_5 for 24 hours at 650°C to liberate oxygen which was reacted with carbon to form carbon dioxide and analyzed on an isotope ratiomass spectrometer. The analyses are reported in the familiar delta value relative to Standard Mean Ocean Water (SMOW) (Craig 1961). Dr. K. Muehlenbachs performed the analyses.

Results and Discussion

The $\delta^{18}O$ values of the five samples of quartz analyzed are shown in Table I. The values obtained range from 12.3 to 13.4 per mil. Kerrich (1980) has obtained values in the range 10.8-13.6 per mil for vein quartz from several deposits in the Yellowknife area; K. Muehlenbachs has obtained results ranging from 10.8-11.9 per mil for vein quartz from the Con mine (unpublished data). One reason for this preliminary study was to determine if auriferous veins could be distinguished from barren veins on the basis of their oxygen isotope values, as has been suggested possible (Akopyan et al. 1976, Golding and Wilson 1980). To test this proposal two of the samples analysed were taken from barren irregular quartz veins within the same terrain. The results of this study show that no clear distinction can be made between gold-bearing veins and barren veins in the Yellowknife district using this method.

However it is noticeable that the values obtained from the veins within medium grade metamorphic rocks are approximately 1

TABLE 1

OXYGEN ISOTOPE DATA FOR QUARTZ

Sample Location and Number	Metamorphic grade of country rocks	$\delta^{18}O$ vein quartz
Camlaren 6	Low	13.4
Barren vein 1	Low	13.3
Tom 4	Medium	12.3
Ptarmigan 1	Medium	12.3
Barren vein 2	Medium	12.5

The location of the barren veins is given in Figure 13.

The analytical uncertainty amounts to 0.2 per mil.

permil lighter than those from veins in low grade rocks. This is not surprising if the veins genesis is related to the metamorphism, for it suggests a higher temperature of equilibration in the medium grade metamorphic rocks (Faure 1977). A similar pattern is noted for regional quartz segregation veins in pelitic rocks of the Homestake mine area (South Dakota). Quartz veins in medium grade metamorphic rocks have $\delta^{18}O$ values about 3 permil lighter than those for veins in lower grade rocks (Rye and Rye 1974).

Oxygen isotope data, from the literature, for quartz veins of the Yellowknife district are summarized in Table 2; note that the single value for the Ptarmigan occurrence is similar to that found in this study. Analysis of mineral equilibrium pairs allows isotopic temperatures and values for $\delta^{18}O$ fluid to be calculated and these data of Kerrich and co-workers are included in the table. However, these researchers have used an early value of the oxygen isotope fractionation factor for the quartz-water system (Clayton et al. 1971). Quite different values are obtained using the preferred, revised Clayton et al. (1972) fractionation factor (in Friedman and O'Neil, 1977). Recalculation gives an isotopic temperature of 360°C for Ptarmigan and values of 325-360°C (quartz-muscovite) and 355-390°C (quartz-chlorite) for the Con mine.

The difference between the isotopic temperature for Ptarmigan and the temperatures of homogenization of fluid inclusions in samples from Ptarmigan (this study) is some 50-120°C. This suggests, assuming the samples used in the different studies to be similar, a pressure of ~0.6 to ~1.4 kbar (60-140 MPa) at the time of formation (data for a 5 weight percent NaCl solution, Potter 1977).

TABLE 2

OXYGEN ISOTOPE DATA

(Kerrich and coworkers)

Location	$\delta^{18}O$ vein quartz	$\delta^{18}O$ mineral	$\Delta^{18}O$ quartz-mineral	T°C*	T°C**	$\delta^{18}O$* fluid	$\delta^{18}O$** fluid
Con mine	11.50 - 12.53	---	3.5 - 3.8 (a)	400 - 450	325 - 360	---	
		5.97-6.58(b)	5.53-5.95(c)	440 - 480	355 - 390	7.9 - 8.2	6.7 - 6.9
Ptarmigan	12.60	6.67 (b)	5.93 (c)	440	360	8.2	7.0

(a) $\Delta^{18}O$ quartz-muscovite

(b) $\delta^{18}O$ chlorite

(c) $\Delta^{18}O$ quartz-chlorite

Data from: Kerrich (1980), Kerrich et al. (1980)
Hutchinson et al. (1980 and Kerrich and Fryer (1981).

Errors in the calculated isotopic temperatures amount to ±30°C.

* Isotopic temperatures and $\delta^{18}O$ fluid values calculated from the equations given by Wenner and Taylor (1971), O'Neil and Taylor (1969) and, supposedly, Clayton et al. (1972). However Kerrich and coworkers have apparently used an earlier equation of Clayton et al. (1971).

**Based on Wenner and Taylor (1971), O'Neil and Taylor (1969) and revised Clayton et al. (1972) In Friedman and O'Neil (1977).

Similarly recalculating the $\delta^{18}O$ fluid values gives a $\delta^{18}O$ fluid of 7.0 permit for Ptarmigan and 6.7 to 6.9 permil for the Con mine. Unfortunately these values do not provide conclusive information on the source of the hydrothermal fluids. Primary magmatic waters have a restricted range of $\delta^{18}O$ (+5.5 to +10.0) whilst metamorphic waters have a wide range (+4 to +25) (Taylor 1979). The values for the veins in the Yellowknife district fall within the overlap between the two types; the data are compatible with either a magmatic fluid or a metamorphic fluid for the formation of the veins.

Conclusions

It is clear from this preliminary study that oxygen isotope analysis alone cannot determine the specific source of the mineralizing fluids. Neither can it be used as a straightforward evaluation tool. Nevertheless a detailed oxygen isotope study of the veins and of the host metasediments could provide a better understanding of the relationship between the two and of the formation of the veins.

6. DISCUSSION AND SUMMARY

Origin of the Gold Mineralization

Various hypotheses have been forwarded for the origin of the gold veins in the Yellowknife district.

Henderson and Jolliffe (1939) proposed that the veins in the sediments were genetically connected with some Precambrian granite and that the veins in the volcanics owed their origin to a deep-seated magmatic source.

Such a magmatic-hydrothermal origin was also supported by Coleman (1957) but in a series of papers culminating in a substantial memoir Boyle (1955, 1959, 1961) proposed a different genesis. He concluded that the veins in the volcanics were derived by lateral secretion into dilatant zones during regional metamorphism. He also applied this model to the auriferous veins in the sedimentary rocks.

Various authors (Ames 1962, McConnell 1964, Chary 1971) challenged Boyles conclusions and--in part through reinterpreting Boyles data--supported a magmatic-hydrothermal origin. However, general disenchantment with classic magmatic-hydrothermal theories, largely due to the recognition of syngenetic features in various ore deposits, along with studies of gold mineralization elsewhere provided increased support for Boyle's proposal of lateral secretion as an important ore-forming mechanism.

The controversy over the origin of the veins has recently

been reopened by the studies of Kerrich and coworkers (Kerrich et al. 1977, Kerrich 1980). They proposed that the shear zones in the volcanics acted as high-permeability conduits along which convective fluid flow was concentrated. The fluids were derived at depth from dehydration reactions in the amphibolite metamorphic zone and deposited gold and silica as they rose and cooled.

This model is in many ways not greatly dissimilar from that of Boyle, for he also considered that the shear zones channelled fluids from depth, but he advocated a significant contribution of ore and other elements from the surrounding country rocks by diffusion processes leading to lateral secretion.

To determine which of these models (if any) is compatible with the collected data and most applicable to the veins of the present study, it is pertinent to briefly review information, derived from experimental studies and descriptions of gold mineralization elsewhere, on the source, transport and deposition of gold, and to discuss these observations with respect to the Yellowknife district.

Source of the Gold

The source of gold in vein deposits has been much considered in the literature, but proposals offered are normally quite speculative for it is unusual that the source can be identified with any certainty.

Viljoen et al. (1970) and Pyke (1975) have suggested a

connection between gold vein deposits and ultramafic rocks on the basis that these rocks have a high primary gold content. Similarly Stephenson and Ehmann (1971) tentatively propose mafic intrusions as a source of gold for Archean mineralization in Manitoba. However more recent work suggests that in most cases ultramafic rocks do not have above average gold contents (Anhaeusser et al. 1975, Kwong and Crocket 1978, Tilling et al. 1973) and the study of Kwong and Crocket indicates that for a greenstone belt in northern Ontario the gold abundance in unaltered volcanic and sedimentary rocks is typically less than 2 ppb.

Boyle (1976)--considering the typical content of gold in unaltered rocks of greenstone belts to range from 5-12 ppb--illustrated how carbonatization or granitization (i.e. ultrametamorphism) can release enormous amounts of gold and suggested that there is no problem in deriving gold; i.e. normal rocks can be the source of gold. Nevertheless it is obvious that if there does happen to be a primary concentration of gold it will increase the likelihood of a secondary concentration occurring (perhaps in the form of gold-quartz veins). In this respect sulphide schists, iron formations, intrusive quartz feldspar porphyries and sulfide-rich carbonaceous shales were offered as the most favourable source rocks (Boyle 1976).

Applying this to the metasediments of the Yellowknife district it is possible the carbonaceous shales acted as source-rocks, though given that the greywackes formed from erosion of felsic

volcanic and intrusive rocks (Henderson 1975) it is unlikely that their initial gold content was particularly low.

Transport and Deposition of the Gold.

Experimental studies of gold transport suggest that gold may be transported either as a chloride complex or as a sulphide complex.

Transport as a chloride complex is favoured in high temperature, acidic, oxidizing solutions (e.g. Helgeson and Garrels 1968, Henley 1973) while sulphide complex transport is more likely in lower temperature, alkaline, less-oxidizing solutions (Weissberg 1970, Rytuba and Dickson 1974). Seward (1973) demonstrated that at temperatures below 350°C maximum gold solubility in approximately neutral pH solutions (considered most comparable with ore-forming fluids) will be achieved with thio complexes.

At high temperatures with gold highly soluble in chloride solutions buffered at an oxygen fugacity generated by the hematite-magnetite pair, deposition of the gold can be brought about by cooling or by changes to lower fugacity (Henley 1973). At lower temperatures with gold existing as thio complexes, deposition of gold can be brought about by decreasing temperature, change in pH or an increase in oxygen fugacity (Rytuba and Dickinson 1974, Seward 1973).

Which of these methods of transport was operable in the Yellowknife district cannot be ascertained from the data collected in this study. The chloride composition of the hydrothermal fluid is indicated by the fluid inclusion data, but the observations of

Ramsay (1973) suggest that the fluid which deposited the barren veins also had a similar composition. It is noticeable that the barren veins do not contain sulphide minerals and this lack of gold and sulphur suggests that sulphur species may have played a predominant role in complexing and transport of the gold.

Considering the high carbon dioxide content of the hydrothermal fluid, another possibility is that of gold transport by carbonate or bicarbonate complexes. Such complexes may be important in the transport of uranium (Langmuir 1978) and have been suggested for the transport of tungsten (Higgins 1980) but the possibility of similar complexes being important in gold transport has apparently received little experimental study.

Factors important in causing the deposition of gold in the Yellowknife district are difficult to discern. From experimental work Henley (1973) and Rytuba and Dickinson (1974) suggest temperature may be important and this would certainly answer why the veins occur mainly near the cordierite isograd. Such a limited spatial distribution has been noted in numerous districts of gold-quartz vein mineralization in metasediments. For example, the gold districts of Lena, USSR (Buryak 1967), New Zealand (Williams 1965) and Nova Scotia (Taylor and Schiller 1966).

Given that the gold-quartz veins at Yellowknife tend to form in dilatant zones--fractured or sheared slate horizons, the noses of folds--decrease in pressure may have been of significance in making gold complexes unstable and bringing about deposition.

However based on experimental studies Seward (1973) considered it of limited importance.

A reduction in oxygen fugacity would also likely cause deposition of gold though its role in the Yellowknife district is difficult to evaluate. However the association of the gold mineralization with blue, dark grey, or black quartz (i.e. quartz containing graphite or amorphous carbon) is notable (Boyle 1953). Such an association has been observed in numerous gold districts (e.g. Thorpe 1975) and in some deposits it has been possible to quantify the relationship between gold and carbon (Mel'nikov 1980, Zakharova 1975). This would suggest reduction of oxygen fugacity is important in gold deposition. Consequently the slate (and carbonaceous biotite schists) may not only have provided an important structural control (acting as a relatively impermeable barrier, or as a dilatant zone due to fracturing, shearing or folding) but also a chemical control on the deposition of the gold.

"Boiling" or fluid immiscibility may also have encouraged the instability of the transport complexes, particularly if carbonate complexes were involved. However "boiling" has been noted in barren veins (e.g. Crawford et al. 1979) and is not always associated with ore deposition in vein deposits (Spooner 1981).

Summary

In summarizing this information and the data from the fluid inclusion study the following model, similar to those of Petrov et al.

(1972) and Henley et al. (1976), can be outlined.

A hydrothermal fluid of high temperature and relatively low salinity, derived from dehydration accompanying amphibolite grade metamorphism of the sediments, migrated upwards through the rock sequence carrying gold dissolved from the country rocks. On decreasing temperature, pressure and oxygen fugacity the gold complexes became unstable depositing gold at moderate temperatures. The temperatures of deposition (in the order of 250-350^{o}C) along with wall rock alteration and structural considerations suggest the mineralization took place after the peak of metamorphism as temperatures were declining and compressional forces were released.

Later stage hydrothermal fluids were of low temperature and moderate to high salinity. These fluids are similar both in Th and salinity to fluids responsible for Mississippi Valley-type mineralization; their age is unknown and they could represent a Proterozoic or Phanerozoic event. The observation of Boyle (1969) that gold is sometimes associated with secondary inclusions suggests that these late stage fluids partially remobilized some of the gold.

Conclusions

The chief conclusions of this work are as follows:

1) Fluid inclusions and oxygen isotope data, along with consideration of the appropriate phase systems, indicate that deposition of the quartz veins and associated gold mineralization occurred from a fluid of moderate temperature (250-350^{o}C) and low salinity ($\sim$5 weight percent NaCl equivalent) at a minimum pressure of about

1 kbar (100 MPa).

2) A later stage hydrothermal fluid was of low temperature ($\sim$140^{o}C) and moderate to high salinity ($\sim$11-30 weight percent NaCl equivalent) and partially remobilized the gold.

3) The data from this study alone are inconclusive but considered in conjunction with published work, leads the author to favour gold-quartz vein formation through metamorphogenic processes, largely in the way that Fyfe and Henley (1973) and Henley et al. (1976) have outlined.

4) With regard to future studies further extensive fluid inclusion research does not appear warranted considering the poor quality of the sample material and contained inclusions. Nevertheless, a detailed study of a single deposit involving research on fluid inclusions, oxygen isotope and wall rock alteration, along with observation of the distribution of gold and carbon species (notably C, CO_2 and CH_4), could provide significant information on the genesis of such deposits. The reopening of the Camlaren mine could provide an ideal opportunity for such a study.

On a more general aspect, the author, through this study and associated literature reviews, considers that the role of carbon (i.e. C, CO_2, CH_4, CO_3^{2-}, HCO_3^{-}) in the transport and/or deposition of gold deserves further research.

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APPENDIX I

BRIEF NOTES ON THE GOLD OCCURRENCES STUDIED

The following brief notes are compiled from various sources including field observations. Further information on these and other gold occurrences of the Yellowknife district, particularly details of their exploration and development history, can be found in the following references: Baragar 1961, 1962; Baragar and Hornbrook 1963, Boyle 1961, Gibbins et al. 1977, Henderson and Jolliffe 1939, Lord 1951, McGlynn 1971, Padgham et al. 1975, 1976; Schiller 1965 and Thorpe 1972.

Occurrences in Low Grade Metamorphic Rocks

AM

This occurrence is located on the southern shore of Knight Bay on the west side of Gordon Lake (Figure 8), approximately 75 km NE of Yellowknife. The property reportedly has five known gold showings (McGlynn 1971), of these the main East (#1) and West (#2) zones were examined. These vein systems outcrop on a small peninsula within the AM 1 claim and are exposed in eight small trenches.

The host rocks are isoclinally folded low grade metagreywackes and slates, with the bedding trending 110-130^{o}. The quartz veins are subparallel to the bedding and appear to occur near the nose of plunging fold which is indicated to be a syncline by graded bedding. The East zone is about 50 m long and consists of quartz veins in a sheared zone up to 50 cm wide. This zone contains graphitic material

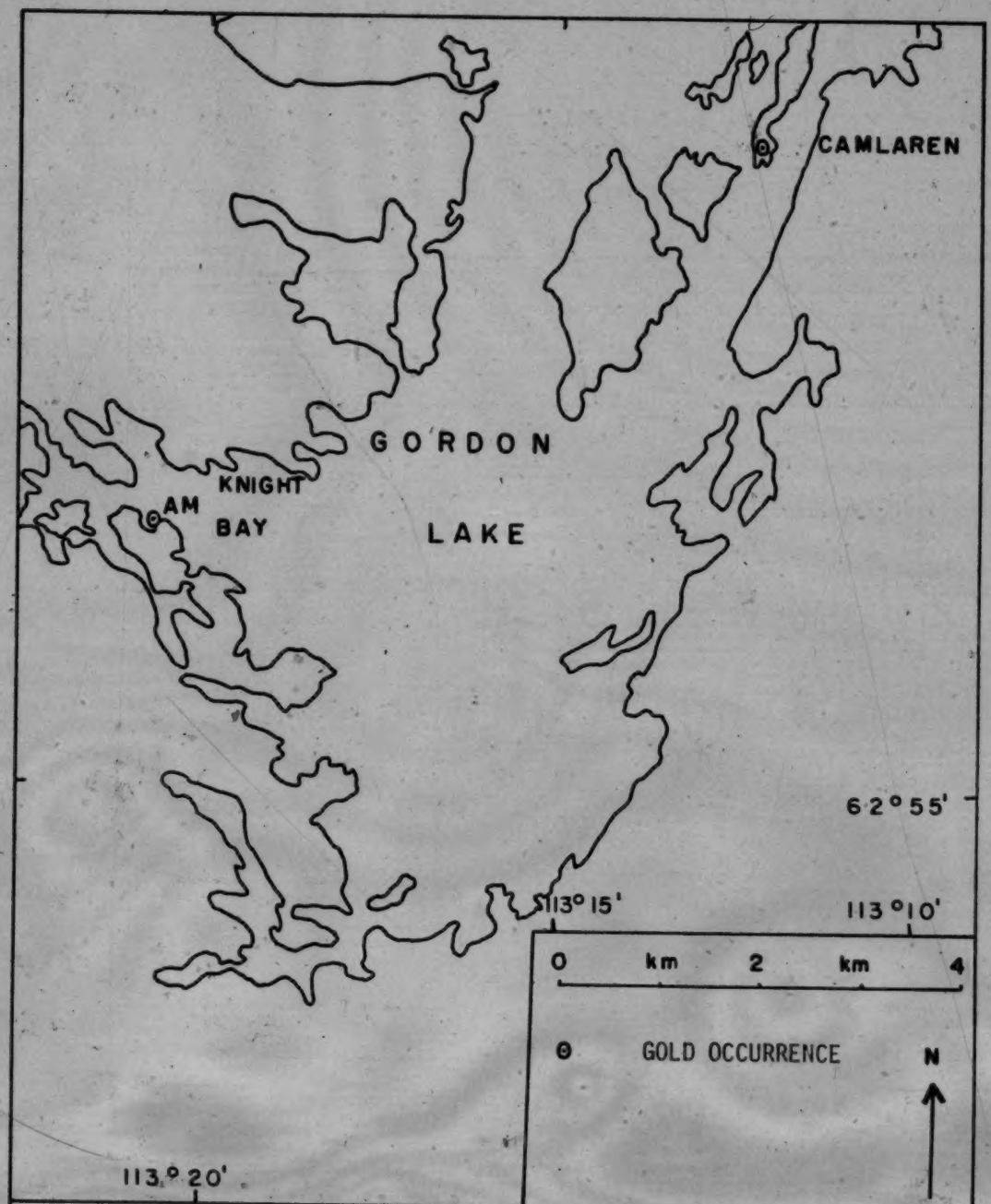


FIGURE 8: Location of the AM and Camlaren gold occurrences.

and the quartz is dark grey to bluish in colour. Minor pyrite, galena and visible gold were observed, while arsenopyrite and sphalerite have also been reported (McGlynn 1971). The West zone, about 70 m long and 30-50 cm wide, is similar in character. (See Figure 9).

Camlaren

The Camlaren mine is situated approximately 85 km NE of Yellowknife on the east side of Gordon Lake (Figure 8). The property is underlain by low grade metagreywackes and slate in which numerous quartz veins, parallel to bedding, occur. The host rocks are isoclinally folded and strike 020-045^{o}. First developed in the late 1930's the mine has recently reopened. At the time of visiting however the mine was closed and samples, some containing visible gold along with pyrite, galena and sphalerite, were collected from the 'ore' stockpile.

There are three main auriferous quartz veins delineated, the most important of which is the Hump vein (Henderson and Jolliffe 1939). This vein occurs in a zone of thinly bedded slate and metagreywacke, in part paralleling the bedding and part concentrated in the nose of a fold which plunges steeply to the NE (Figure 10). The vein is 1-1.5 m at surface, though widens to 6 m in the saddle of the fold. The quartz is light blue-grey in colour and graphite-coated shear surfaces have been noted within the vein and at its contacts (Henderson and Fraser 1948). The gold is generally associated with the sulphides (which constitute less than one percent of the vein); chalcopyrite has also been reported.

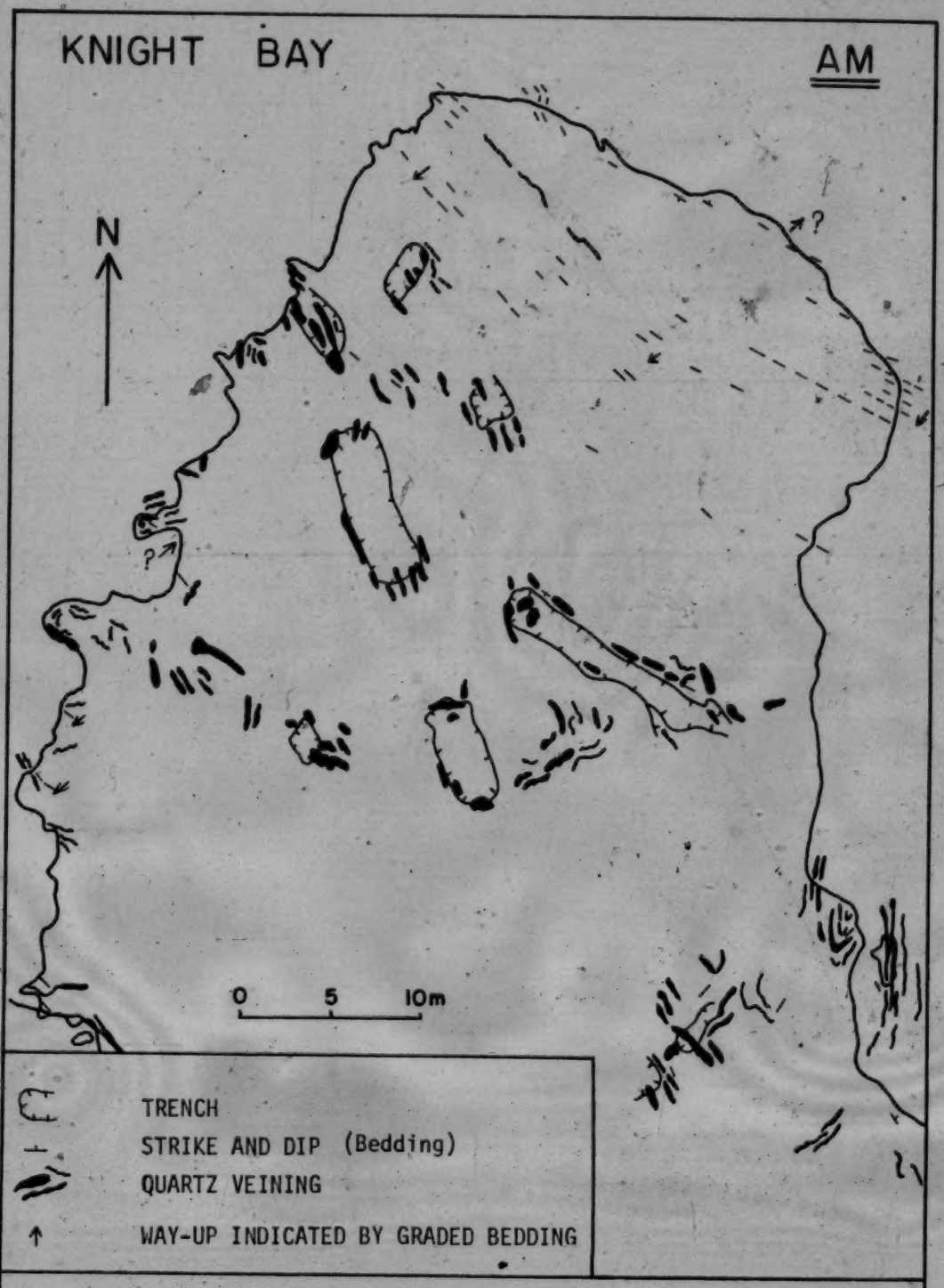


FIGURE 9: Geological sketch map of the AM occurrence. July 1976.

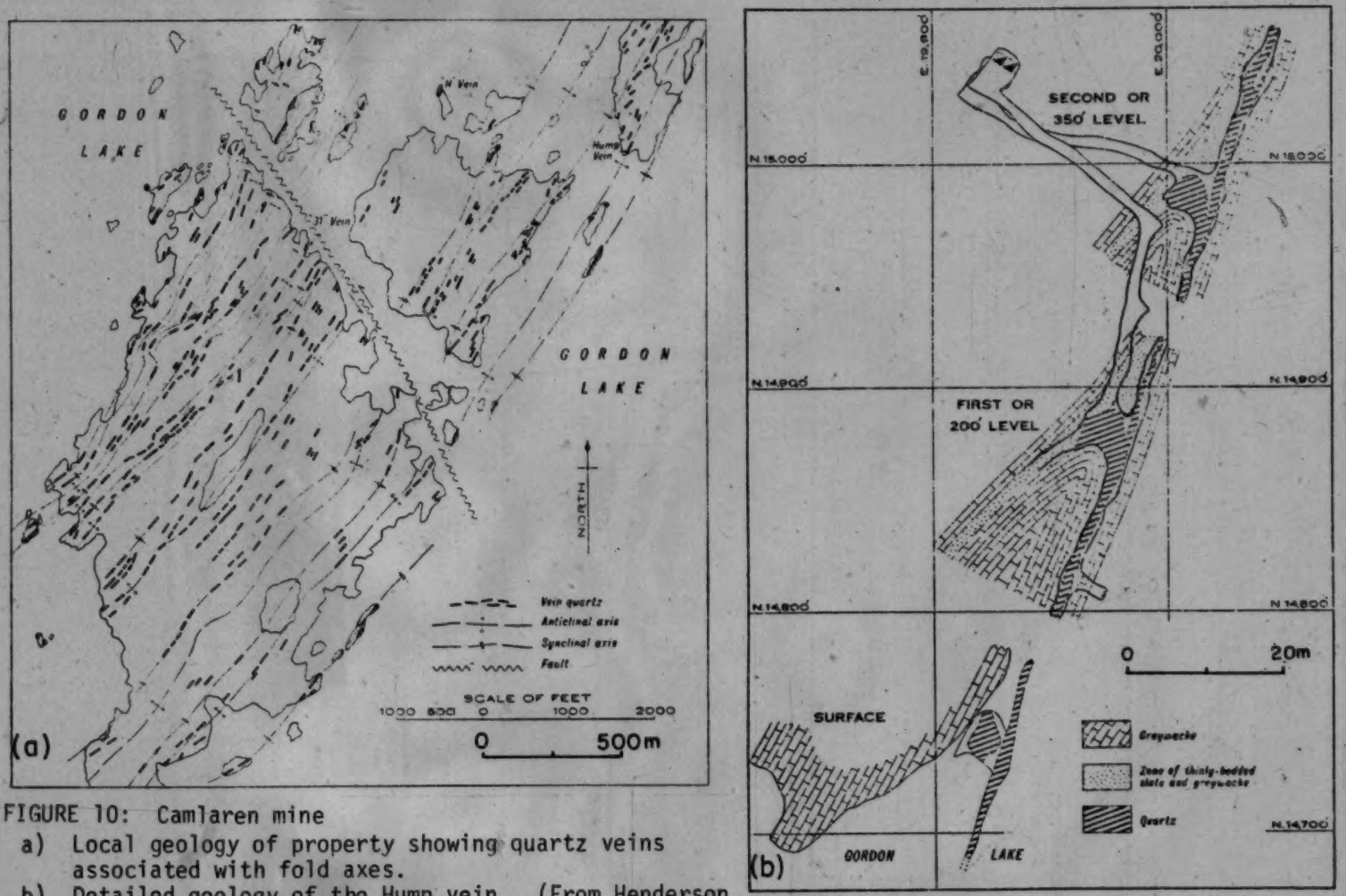


FIGURE 10: Camlaren mine

a) Local geology of property showing quartz veins associated with fold axes.

b) Detailed geology of the Hump vein. (From Henderson and Jolliffe 1939).

In the early sixties about 12,000 tons of ore was milled, grading just over 1 oz. per ton. As of 1975, reserves were estimated at 56,000 tons grading 0.62 oz. per ton of gold (Gibbins et al. 1977).

Joon

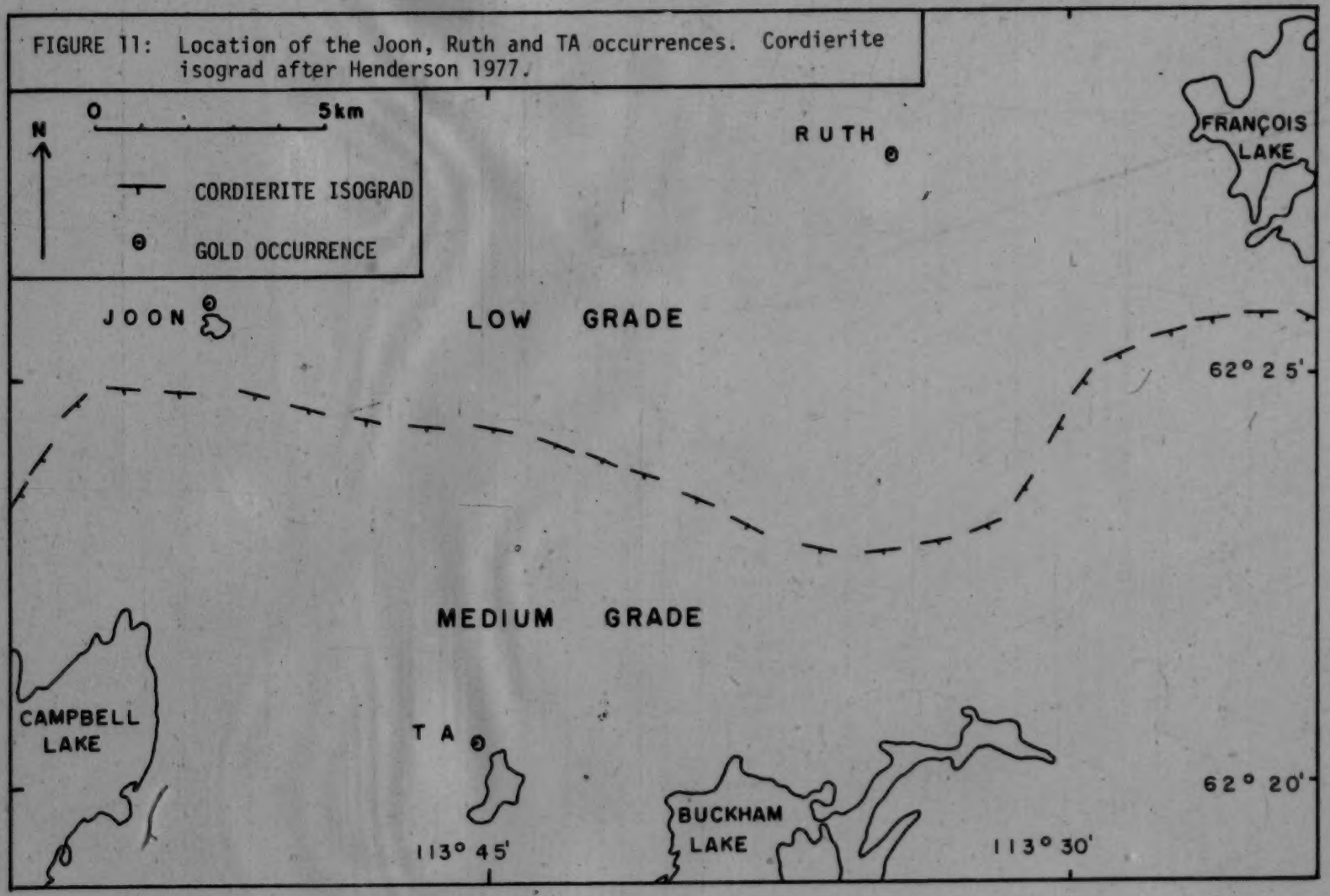
This occurrence is about 75 km E of Yellowknife, immediately N of "Strike Lake". The host rocks are low grade metagreywacke and slate which strike 140-150^{o} and dip steeply to the east. The mineralization occurs in two main zones: the West zone, ~60 m by 5 m and the East zone ~30 m by 0.5 m, at surface. These consist of narrow quartz veins subparallel to the bedding and associated with minor shearing in a graphitic slate horizon. The quartz is blue-grey in colour and contains minor pyrite and visible gold which are mainly found at the vein contacts. (See Figures 11 and 12).

'Ore' reserves have been estimated at about 2,000 tons grading 2 oz. of Au per ton (Padgham et al. 1976) and in the late seventies production amounted to 300 oz of Au from hand sorted ore.

Ruth

Located nearly 95 km east of Yellowknife, the Ruth property is underlain by steeply dipping folded, low grade metagreywacke and slate. There are over 90 trenches on six veins within the property but most development work has been on three of these veins. In this study samples for fluid inclusion study were collected from one of these three veins, the #2 vein, in the vicinity of the old shaft.

FIGURE 11: Location of the Joon, Ruth and TA occurrences. Cordierite isograd after Henderson 1977.



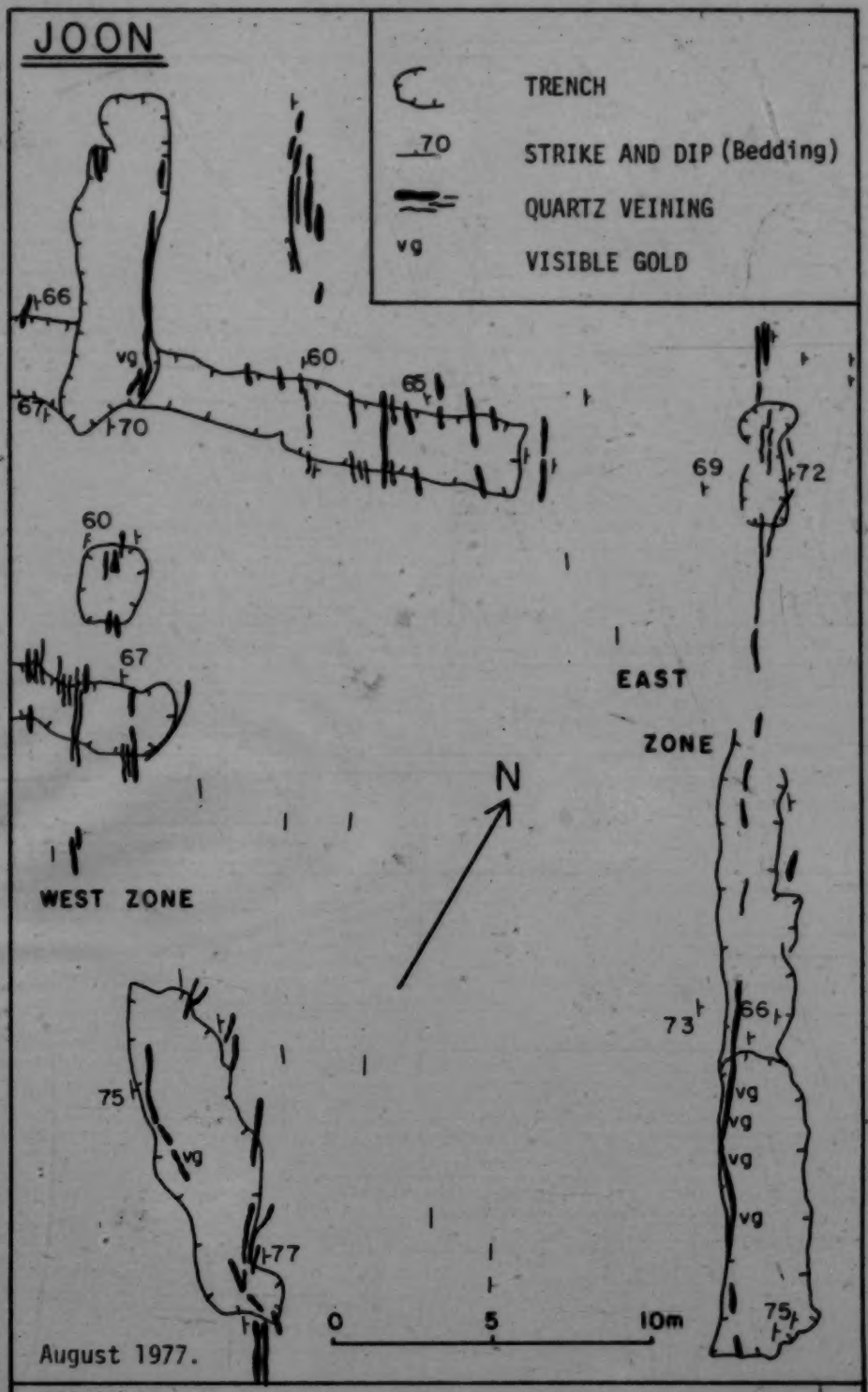


FIGURE 12: Geological sketch map of the Joon occurrence.

The #2 vein is hosted by steeply dipping strata which strike 000-020^{0} and face east (indicated by well-developed graded bedding). The vein subparallels the bedding, occurs mainly within a slate horizon and is exposed for some 400 m, being 30-40 cm wide. Wall rock alteration is very minor there being slight development of biotite and arsenopyrite. The quartz is fine grained, white to grey in colour, with occasional biotite inclusions and contains minor pyrite and visible gold. Lord (1951) recorded the presence of scheelite also.

The #2 vein has been estimated to contain approximately 2,500 tons of 'ore' grading 2.2 oz of Au per ton (Padgham et al. 1976).

Occurrences in Medium Grade Metamorphic Rocks

Ptarmigan

The Ptarmigan mine is situated 10 km NE of Yellowknife, south of Prosperous Lake. A number of quartz veins occur en echelon hosted by a quartz mica schist, the higher grade equivalent of the metagreywacke and slate. Relict bedding indicates a strike of about 170^{0} for these rocks; they dip steeply east and are overturned. (See Figure 13).

The main auriferous vein (#1) cuts across the bedding, striking at 115^{0} and is exposed discontinuously for 400 m and averages 4 m in width. The quartz is mainly light to dark grey, coarse grained and vitreous. Even in hand specimen it can often be

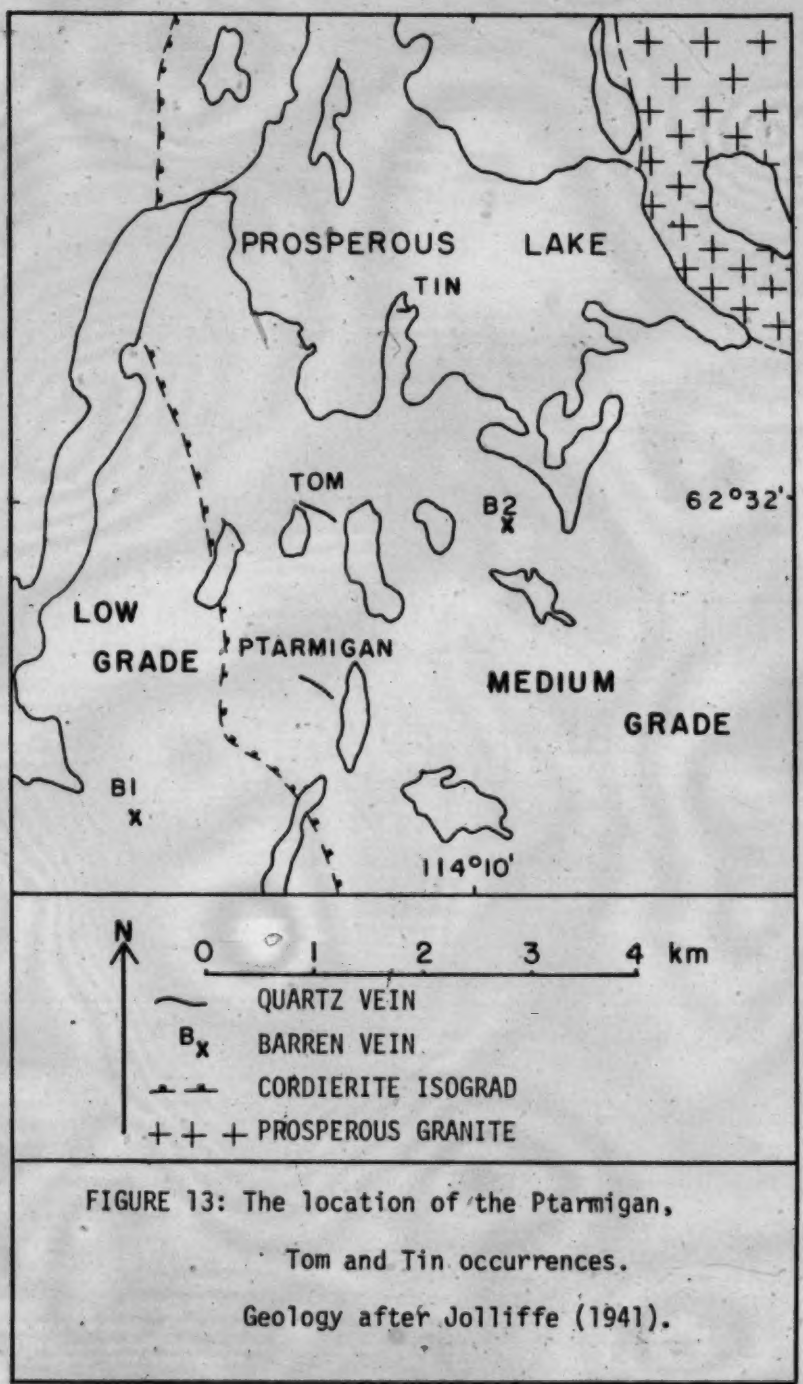


FIGURE 13: The location of the Ptarmigan, Tom and Tin occurrences. Geology after Jolliffe (1941).

seen that the colour is caused by disseminated black specks. Milky white quartz veinlets also occur; Boyle (1961) considered these to be later than the grey, glassy quartz but as Ramsay (1973a) noted the relationship is not always clear. Tourmaline and well developed biotite occur sporadically along the vein contacts. Visible gold is generally associated with sulphide mineralization; pyrite, galena and sphalerite are the most common. Boyle (1961) recorded arsenopyrite, chalcopyrite and pyrrhotite as well, along with scheelite. During 1941-1942 about 35,000 tons of ore were milled, averaging approximately 0.34 oz. of Au per ton (Lord, 1951).

Tom

This property is just N of the Ptarmigan mine, some 12 km from Yellowknife. The mineralization is hosted by quartz mica schist; relict bedding is steeply dipping and strikes 170-180°, indistinct graded bedding suggests the strata face west. (See Figure 13).

The main auriferous vein (#3) is very similar to the Ptarmigan veins and may represent a continuation of that system. The vein outcrops for approximately 400 m and averages 2 m wide; it crosscuts the bedding, striking at 110-120°. The quartz is white to dark grey in colour and varies from saccharoidal to coarse-grained. Pyrite, galena and visible gold were observed in samples taken from a small dump around the shaft. Wall rock alteration is limited to the development of coarse biotite, pyrite and traces of pyrrhotite. Minor quartz-tourmaline veinlets occur alongside the main vein, they are discontinuous and irregular and their relationship to the

main vein is uncertain.

Tin

The Tin occurrence is on the south shore of Prosperous Lake, about 13 km NE of Yellowknife. The host rock is quartz mica schist which exhibits bedding which strikes 010-030° and the beds dip steeply to the west. The mineralization is largely within a 1 m thick, yellow-weathering sericite schist perhaps representative of a small shear or fault which crosscuts the bedding. Massive dark grey to black sphalerite is common and occurs along with ankerite, minor pyrite and traces of visible gold and pyrrhotite. The presence of chalcopyrite is suggested by minor malachite staining. Associated with this mineralization, which is exposed in a trench about 10 m long, are numerous subparallel veinlets of white to dark grey quartz. Outside of the sericite schist zone these veins are edged with well-developed biotite. No production is reported from this small showing. (See Figure 13).

TA

The TA property is situated 84 km ESE of Yellowknife, just north of Bullmoose Lake. The country rocks vary from coarse-grained quartz mica schist to finer grained biotite schist representing the metamorphosed equivalents of greywacke and shale. (See Figure 11).

Seven main veins occur on the property but most of the development work was carried out on the #4 vein and this is the one that was sampled. The vein strikes approximately 165° and dips

steeply to the east, parallel with the bedding. It occurs at the contact between a quartz mica schist and a finer grained biotite schist; minor shearing is exhibited all along the vein. South of an old shaft the vein averages 10 cm in width, ranging up to 30 cm; north of the shaft it is wider, 2-5 m, though is partially obscured by rubble. Overall length is about 150 m. The quartz varies from a fine-grained white type to a dark grey vitreous variety; pyrite and traces of visible gold were the only metallic minerals noted. Wallrock alteration is limited to the development of coarse-grained biotite. Production has been limited to a little hand-sorted ore in 1940-1941 (Lord 1951).

Hidden Lake

This showing is located 45 km ENE of Yellowknife, north of the east end of Hidden Lake. The country rocks consist of thinly bedded quartz mica schists which strike 150-170^{o} and dip at 25-30^{o} east. Little is visible at surface, but underground development work indicates the mineralization is found in a series of quartz boudins which subparallel the bedding (Schiller 1965). Reported metallic minerals are pyrite, galena, chalcopyrite and visible gold. Tourmaline and biotite occur as alteration minerals at the margins of the quartz veins. Samples were collected from several small pits about 20 m W of an old shaft. Drilling results suggest the mineralization is of very limited extent (Padgham et al. 1976).

Barren veins

Numerous small, irregular bodies of vein quartz occur in the metasediments in the Yellowknife area; as far as is known they do not contain any gold mineralization and are thought to have formed during metamorphism (Boyle 1961, Ramsay 1973a). In a study of quartz from these veins Ramsay (1973a) determined a main range of Th of 210-270^{o}C for primary inclusions and of 115-165^{o}C for secondary inclusions. No freezing studies were performed but he noted that many of the secondary inclusions were saturated at room temperature; he suggested that the primary inclusions were slightly undersaturated. The types of inclusions that he noted are broadly similar to those observed in this study.

APPENDIX II

FLUID INCLUSION METHODOLOGY

Instrumentation

The equipment used in this study was a Chaixmeca microthermometry apparatus (model VI 2120) specifically designed for the study of fluid inclusions. It consists of a combined heating and freezing stage, with sample chamber, and a console with temperature read-out and controller.

The bronze alloy stage is heated using an annular resistance heating coil; cooling is achieved by a flow of nitrogen gas through the stage. The gas is first cooled by passing it through a copper coil within a liquid nitrogen bath. The stage contains a platinum resistance thermal sensor which is connected to a digital voltmeter having a resolution of $0.1^{o}C$. The equipment can be used in the range $-180^{o}C$ to $+600^{o}C$.

The heating-freezing stage is attached to a Leitz microscope and is used with 5x, 10x, 20x, 32x and 40x lenses, and 25x and 10x oculars. The 20x and 32x lenses have been fitted with water jackets so that they can be cooled by circulating water during high temperature use of the stage.

A plastic sleeve can be fitted between the lens and the sample chamber to improve insulation and decrease frosting when using the stage at low temperatures. Illumination of the fluid inclusion samples may be improved by using an American Optical

Corporation flexible fibre-optics illuminator.

A small black and white television camera has been fitted to the microscope so that the inclusions under observation can be displayed on a television screen. This increases operator efficiency by reducing eyestrain, though optical resolution is slightly poorer. When precise observations are necessary the microscope is used directly.

Poty et al. (1976) describe and illustrate a similar microthermometry apparatus. Tests they carried out at 380°C indicate a vertical gradient of 0.9 to 1.0°C over a distance of up to 1 mm above the heating stage. At this temperature tests show that in the optic field of the stage the horizontal thermal gradient was not more than 0.8°C from the centre of the optic field to its edge.

For future studies it would be worthwhile to follow the modifications of Cunningham and Carollo (1980). These include the use of a water jacket for the microscope lens (as has been done), alteration of the sample chamber and thermal insulation of the stage. The modifications result in improved optical resolution, decreased thermal gradients and a more linear calibration curve.

For prolonged use of the stage at high temperatures it would be beneficial to obtain the gold-coated stage available from Chaixmeca. This prevents oxidation of the stage which otherwise may occur under such conditions.

Calibration

Good precision can be achieved using the microthermometry techniques under standard operating procedure. An indication of the possible reproducibility of results is given in Figure 14.

However, to attain accuracy it is necessary to calibrate the instrument. This is done by measuring the melting point of high purity compounds. Surprisingly few compounds are suitable for use: many substances having melting points within the range of interest, dissociate or melt incongruently on heating and some compounds give poor reproducibility due to hydration. The standards chosen and used are listed in Table 3. Jehl (1975, Annex III) discusses calibration and the choice of standards at some length.

For determination of the melting points the standards were sealed within glass capillary tubes. Mainly square and rectangular cross-section capillary tubes of 0.2-0.5 mm internal diameter were used as it was thought these would best approximate fluid inclusion samples, and give better thermal contact than capillary tubes with a circular cross-section.

Sealing the compounds within the glass tubes was a problem, particularly with the volatile organic liquids. In an attempt to solve this a carbon dioxide laser (designed for surgery) was used to fuse and seal the capillaries. The laser provided a high temperature point source of heat, and facilitated rapid fusing of the glass with diminished loss of the compound by

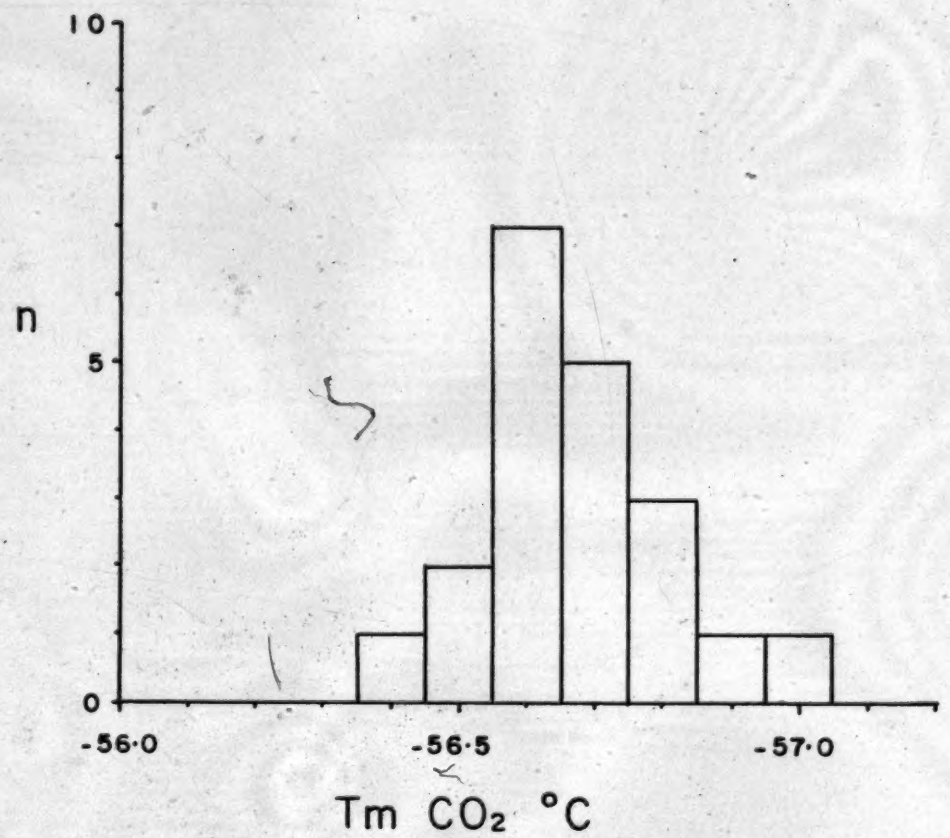


FIGURE 14: Microthermometric stage reproducibility. Plot of 20 measurements of $TmCO_2$ for a single three-phase inclusion in quartz from Camperio, Switzerland. This is an interlaboratory standard and the value of -56.6°C (the triple point of CO_2) is assigned to the peak.

TABLE 3

MOCROTHERMOMETRY CALIBRATION STANDARDS

Name	Formula	Melting Temperature ^{o}C
a) cyclohexene	C_6H_{10}	-103.5
b) heptane	C_7H_{16}	- 90.61
c) octane	C_8H_{18}	- 56.79
d) CO_2 inclusion	CO_2	- 56.6
e) ethylene glycol	$HOCH_2CH_2OH$	- 11.5
f) Merck 9670	?	+ 70
g) Merck 9700	?	+100
h) tin terraoxdide	SnI_4	+144.5
i) ammonium nitrate	NH_4NO_3	+169.6
j) Merck 9780	?	+180
k) Merck 9800	?	+200
l) mercuric bromide	$HgBr_2$	+236
m) Merck 9847	?	+247
n) antimony trifluoride	SbF_3	+292
o) sodium nitrate	$NaNO_3$	+306.8
p) arsenic trioxide	As_2O_3	+315
q) anhydrous sodium acetate	$NaOOCCH_3$	+324
r) potassium dichromate	$K_2Cr_2O_7$	+398
s) thallium bromide	$TlBr_2$	+480

volatilization. Although results were further improved by first freezing the volatile compounds, proper sealing was difficult to attain.

The outside diameters of the capillaries were very close to the average thickness of the fluid inclusion samples, therefore vertical temperature gradients within the heating-freezing stage could be disregarded. Horizontal gradients were minimized by considering only that part of the standard located in the optic centre of the stage. The operating procedure used during calibration (i.e. stage and sample positioning, heating rate, lens, flow rate for water jacket, illumination, etc.) was as close as possible to that used during subsequent examination of the fluid inclusion samples.

A heating rate of 0.25^{o}C per minute was used within 10^{o}C of the target temperature. This approaches static heat-flow conditions and results in lower thermal gradients and reduced errors (Roedder, 1976).

The temperature of melting of the last solid at the optic centre of the stage was taken to be the melting point. This limits the influence of impurities which generally lower the melting point of a substance. Several readings were taken on each standard to check on reproducibility of results.

The results are plotted in Figure 15 as a calibration curve. Figure 16 clearly shows the correction factor that must be applied at any given, recorded temperature. This figure also

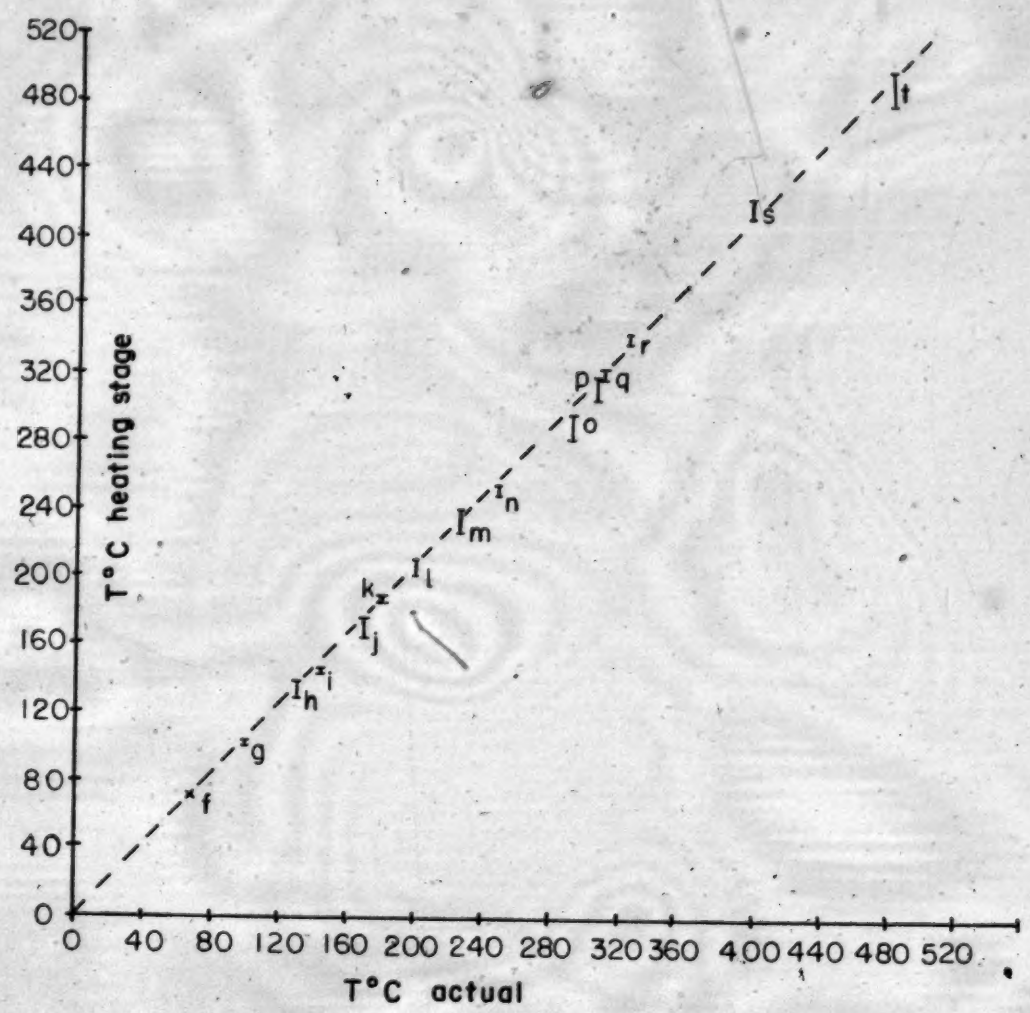


FIGURE 15: Calibration curve for the heating stage. Letters refer to the standards listed in Table 3.

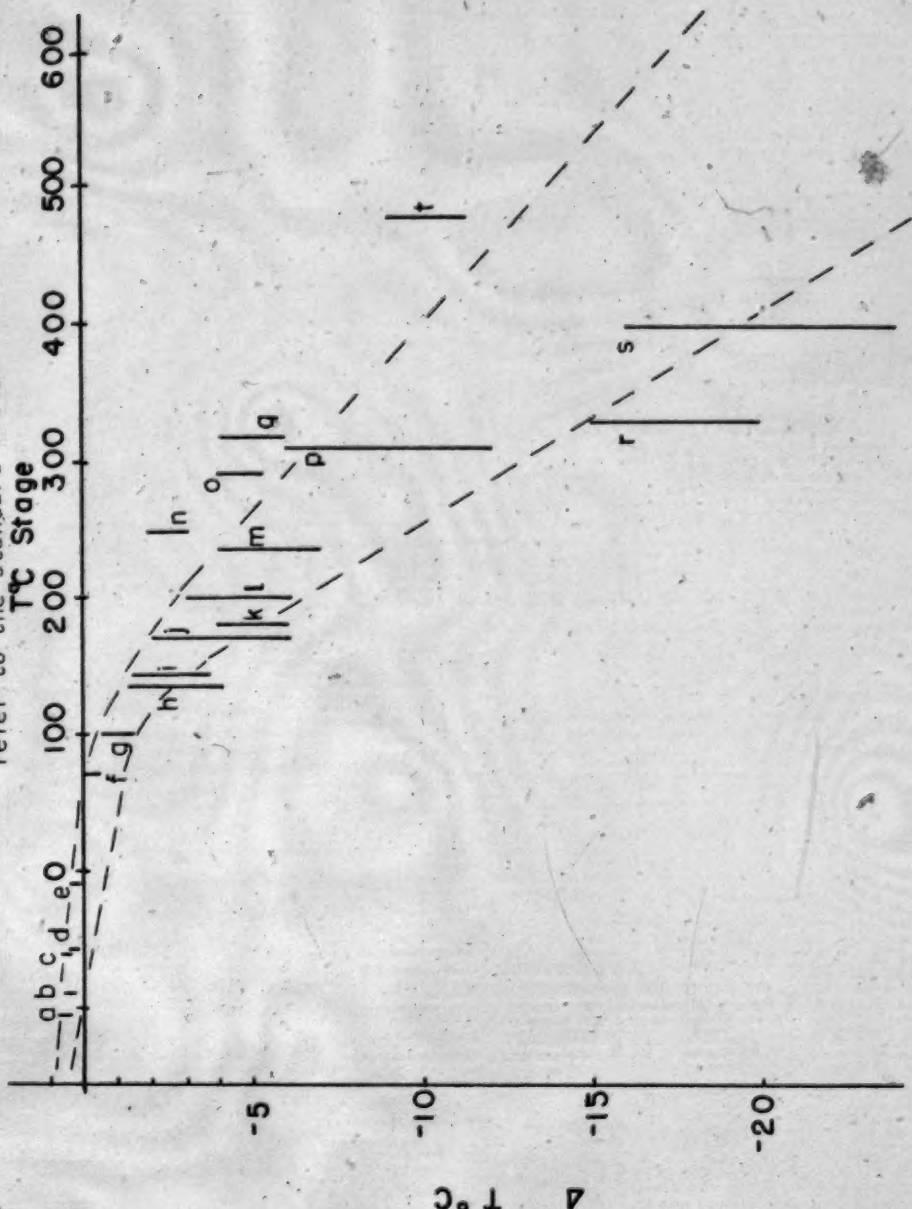


FIGURE 16: Calibration curve showing correction values. Letters refer to the standard listed in Table 3.

demonstrates the decreased reproducibility at high temperatures which is due to the difficulty of achieving low, controlled heating rates at such temperatures.

Discussion of the practicalities of calibrating and using microthermometric equipment is widely dispersed in the literature and often in less accessible sources such as theses. However Roedder (1976) covers some aspects with particular regard to ore deposits and, fortunately, in a recent paper Hollister et al. (1981) compile and review available information. This latter reference is strongly recommended to anyone embarking on a fluid inclusion study.

Crushing Method

Minute grains from the fluid inclusion samples were crushed in a crushing stage while being examined through the petrographic microscope. As first described by Deicha (1950) this method allows the detection of gas under high pressure in fluid inclusions. An adaptation of the technique enables qualitative determination of the gas(es) present.

The crushing stage used is similar to that described by Roedder (1970); he gives details of the design and operation of such a stage. The method allows the detection of the presence of as little as 10^{-14} g of noncondensable gas and the estimate of the confining pressure if the volumes of the gas bubble before and after crushing are compared. Varying the crushing medium can indicate the nature of the gas released upon crushing.

The samples were first crushed in anhydrous glycerine. H_2O is instantly absorbed by the glycerine but CO_2 and many hydrocarbons are insoluble and are visible as small bubbles. By then crushing samples in barium hydroxide solution CO_2 can be identified (Rasumny 1957, 1960). The barium hydroxide reacts with any CO_2 released from the inclusions forming a white precipitate. Alternatively an alkaline barium chloride solution can be used to detect CO_2 (Roedder, 1970). Finally the samples are crushed in CO_2-saturated kerosene; this absorbs hydrocarbons, but not CO_2 which will form small bubbles in the liquid.

Further details of the technique are given in Roedder (1970, 1972). It is worth noting his caution that, with such small volumes of gas, an "insoluble" gas may dissolve in the liquids used--though more slowly than a soluble gas.

The results of the crushing experiments are presented in Table 4.

TABLE 4

CRUSHING RESULTS--GAS EVOLUTION

Sample No.	Crushing Fluid		
	a) Anhydrous Glycerine	b) CO_2 saturated Kerosene	c) Barium Hydroxide
AM			
A1	Minor	No	No
A2	Moderate	No	No
A3	Minor	No	No
A5	Abundant	Minor	No
A6	Moderate	Moderate	Minor
A7	Minor	Minor	No
A8	Moderate	Minor	No
A10	Moderate	Moderate	No
A11	Minor	Minor	No
A12	Abundant	Abundant	Minor
A14	Abundant	Moderate	No
Camlaren			
C1	Abundant	Abundant	Minor
C2	Minor	Minor	No
C3	Moderate	Moderate	No
C4	Abundant	Minor	No
C5	Abundant	Moderate	Minor
C6	Moderate	Minor	No
C8	Minor	Minor	No
C9	Moderate	Moderate	No
C10	Minor	Minor	Minor
C11	Minor	Minor	No
C12	Moderate	Minor	No
C13	Minor	No	No
Joon			
J1	Minor	Minor	No
J2	Moderate	Minor	No
J3	No	No	No
J4	Moderate	Minor	No
J5	Abundant	Moderate	Moderate
J6	Minor	No	No
J7	Moderate	Moderate	Minor
J8	Minor	No	No
J10	Moderate	No	No

Sample No.	Crushing Fluid		
	a) Anhydrous Glycerine	b) CO_2 saturated Kerosene	c) Barium Hydroxide
Ruth			
R2	Abundant	Moderate	Minor
R3	Moderate	Minor	Minor
R4	Minor	No	No
R6	Minor	Minor	No
R7	No	No	No
R8	Minor	No	No
R9	Moderate	Minor	No
R10	Moderate	Minor	Minor
Ptarmigan			
P1	Minor	No	No
P3	Abundant	Minor	Minor
P4	Moderate	Minor	No
P5	Minor	No	No
Tom			
T1	Moderate	Moderate	Minor
T3	Minor	No	No
T4	Moderate	Minor	No
Tin			
S1	Moderate	Minor	No
S1	Moderate	No	No
TA			
D1	Moderate	Minor	No
D4	Abundant	Moderate	Minor
D5	Minor	No	No
D6	No	No	No
D8	Moderate	No	No
Hidden Lake			
H1	Abundant	Moderate	Minor
H2	Minor	No	No
H3	No	No	No
H5	Moderate	Minor	No
H6	Moderate	Minor	Minor
H7	Abundant	Minor	No
H9	No	No	No
H11	Minor	No	No

a) High pressure gas indicator
b) CO_2 indicator } Together may indicate hydrocarbons
c) CO_2 indicator

APPENDIX III

FLUID INCLUSION SALINITY DATA

Locality and Sample Number	Inclusion Class	Number Measured	$Tm^{o}C$ Range	Wt.% NaCl Equivalent
AM				
A1	P	2	-3.2 to -3.7	5.4 - 6.2
	S	2	-5.4 to -6.7	8.5 - 10.1
A2	P	3	-2.6 to -5.1	4.3 - 8.1
	S	2	-7.5 to -13.4	11.1 - 17.2
A3	P	1	-1.9	3.2
	S	3	-.68 to -15.6	10.3 - 19.2
A5	P	2	-2.0 to -2.4	3.4 - 4.0
	S	3	-6.0 to -11.2	9.3 - 15.2
A6	P(?)	1	-1.0	1.7
	S	2	-6.1 to -6.7	9.4 - 10.2
A7	P	2	-1.9 to -2.3	3.1 - 3.8
	S	3	-16.9 to -19.2, +155	20.3 - 30
A8	P	1	-3.0	4.9
	S	2	-12.2 to -15.0	16.1 - 18.7
A10	P	3	-2.9 to -3.5	4.7 - 5.8
	S	3	-4.5 to -9.3	7.2 - 13.3
A12	P	1	-2.6	4.2
	S	2	-5.1 to -11.4	8.1 - 15.4
A14	S	2	-3.7 to -9.2	6.1 - 13.2
Camlaren				
C1	P	1	-1.5	2.4
	S	2	-5.7 to -6.7	8.9 - 10.1
C2	P	1	-2.3	3.8
	S	2	-6.0 to -6.8	9.2 - 10.3
C3	S	2	-5.2 to -10.0	8.2 - 14.1
C4	P	2	-3.7 to -7.2	6.2 - 10.7
	S	3	-6.5 to -8.5	9.9 - 12.3
C5	P	1	-2.4	4.0
	S	2	-6.7 to -8.0	10.1 - 11.8
C6	S	2	-4.8 to -5.2	7.6 - 8.2
C8	P	1	-2.9	4.8
	S	1	-7.7	11.4
C9	P	2	-2.0 to -3.7	3.4 - 6.2
	S	3	-3.8 to -9.2	6.3 - 13.1
C10	P	1	-14.3	18.1
	S	3	-6.7 to -10.1	10.2 - 14.1

Locality and Sample Number	Inclusion Class	Number Measured	$Tm^{o}C$ Range	Wt.% NaCl Equivalent
C11	P	2	-2.6 to -3.8	4.2 - 6.3
	S	2	-6.0 to -8.3	9.2 - 12.1
C12	P(?)	1	-9.0	13.0
	S	2	-7.3 to -7.7	10.9 - 11.3
C13	P	2	-2.4 to -3.3	3.9 - 5.5
	S	1	-16.8	20.2
Joon				
J1	P	1	-3.1	5.1
	S	2	-6.0 to -7.6	9.3 - 11.2
J2	P	2	-3.0 to -3.7	4.9 - 6.1
	S	3	-7.7 to -12.2	11.4 - 16.1
J3	P	2	-2.9 to -8.3	4.8 - 12.1
	S	2	-6.0 to -14.4	9.3 - 18.2
J4	P	1	-6.9	10.4
	S	2	-8.6 to -9.5	12.4 - 13.5
J5	P	1	-3.8	6.3
	S	2	-4.5 to -10.2	7.2 - 14.2
J6	P	2	-1.3 to -1.7	2.1 - 2.8
	S	2	-14.5 to -15.9	18.3 - 19.4
J7	S	1	+143	29
J8	P	1	-4.4	7.1
	S	2	-15.7 to -19.2	19.3 - 22.1
J10	P	1	-2.3	3.8
	S	3	-5.7 to -8.3	8.9 - 12.1
Ruth				
R2	P	1	-2.3	3.7
	S	2	-5.5 to -6.8	8.6 - 10.3
R3	S	1	-8.3	12.1
R4	P	1	-3.4	5.6
	S	2	-6.9 to -11.1	10.4 - 15.1
R6	P	2	-3.0 to -3.5	4.9 - 5.8
	S	3	-12.2 to -15.7	16.1 - 19.3
R7	P	1	-4.4	7.1
	S	2	-6.0 to -6.2	9.3 - 9.5
R8	P	1	-6.7	10.2
	S	2	-5.3 to -8.3	8.4 - 12.1
R9	P	1	-2.5	4.1
	S	3	-6.7 to -18.1	10.1 - 21.3
R10	P	2	-2.3 to -2.4	3.8 - 3.9
	S	2	-6.1 to -7.6	9.4 - 11.2

Locality and Sample Number	Inclusion Class	Number Measured	$Tm^{o}C$ Range	Wt.% NaCl Equivalent
Ptarmigan				
P1	P	2	-2.8 to -3.8	4.6 - 6.3
	S	3	-4.6 to -5.7	7.4 - 10.4
P3	P	1	-3.2	5.4
	S	2	-7.5 to -8.5	11.1 - 12.3
P4	P	2	-4.5 to -5.2	7.3 - 8.2
	S	2	-6.1 to -9.2	9.4 - 13.1
P5	P	1	-1.4	2.3
	S	3	-8.8 to -16.3	12.7 - 19.8
Tom				
T1	P	1	-3.2	5.4
	S	3	-6.5 to -7.9	9.8 - 11.6
T3	P	2	-3.6 to -3.8	5.9 - 6.3
	S	3	-15.0 to -19.2, +183	18.7 - 31
T4	P	2	-2.4 to -2.6	3.9 - 4.2
	S	2	-8.8 to -13.4	12.7 - 17.2
Tin				
S1	P	2	-2.1 to -4.4	3.5 - 7.1
	S	3	-7.2 to -12.3	10.7 - 16.3
S2	P	2	-2.7 to -3.4	4.4 - 5.6
	S	3	-6.5 yo -10.2	9.9 - 14.2
TA				
D1	P	2	-2.5 to -3.4	4.1 - 5.6
	S	3	-5.3 to -12.5	8.4 - 16.4
D4	P	2	-2.4 to -3.7	3.9 - 6.1
	S	3	-6.5 to -9.2	9.8 - 13.1
D5	P	2	-4.4 to -7.5	7.0 - 11.1
	S	3	-7.7 to -14.5	11.4 - 18.3
D6	P	1	-3.0	4.9
	S	2	-4.8 to -5.0	7.6 - 7.9
D8	P	2	-1.9 to -2.9	3.1 - 4.8
	S	2	-5.6 yo -5.9	8.7 - 9.1
Hidden Lake				
H1	P	2	-2.8 to -3.7	4.6 - 6.1
	S	3	-4.6 to -8.4	7.4 - 12.2
H2	P	1	-3.5	5.8
	S	2	-6.5 to -12.7	9.8 - 16.7

Locality and Sample Number	Inclusion Class	Number Measured	Tm°C Range	Wt.% NaCl Equivalent
H3	S	3	-5.5 to -7.5	8.6 - 11.1
H5	S	2	-3.7 to -6.0	6.2 - 9.3
H6	P	2	-2.0 to -4.4	3.4 - 7.1
	S	2	-6.7 to -8.6	10.2 - 12.4
H7	P	2	-3.2 to -11.2	5.2 - 15.2
	S	2	-6.2 to -9.2, +134	9.5 - 29
H9	S	2	-5.7 to -5.9	8.9 - 9.1
H11	P	1	-3.0	4.9
	S	3	-6.8 to -11.1	10.3 - 15.1

Negative Tm values are of Tm ice.

Positive Tm values are of Tm NaCl.

APPENDIX IV

FLUID INCLUSION HOMOGENIZATION DATA

Locality and Sample Number	Inclusion Class	Number Measured	$Th^{o}C$ Range	Remarks
AM				
A1	primary	5	209-231	
	secondary	6	107-121	
A2	P	8	213-270	
	S	4	121-144	
A3	P	3	251-253	
	S	6	212-168	
A5	P	6	212-240	
	S	7	126-201	
A6	P(?)	2	211-221	
	S	4	139-151	
A7	P	5	239-267	
	S	8	155-210	
A8	P	3	224-235	
	S	5	122-136	
A10	P	4	253-264	
	S	6	111-148	
A11	S	5	129-134	
A12	P	3	285-301	One vapour phase inclusion
	S	7	129-151	
A14	P	1	310	
	S	4	149-170	
Camlaren				
C1	P	2	302-308	
	S	4	112-151	
C2	P	3	250-264	VG
	S	5	141-202	
C3	P	2	272-286	
	S	3	139-148	
C4	P	4	219-243	
	S	5	129-161	
C5	P	1	245	
	S	6	132-161	
C6	P(?)	1	227	
	S	3	113-141	
C8	P	3	234-256	
	S	3	117-121	
C9	P	5	224-274	VG
	S	6	125-176	

Locality and Sample Number	Inclusion Class	Number Measured	Th°C Range	Remarks
C10	P	3	212-274	
	S	6	131-170	
C11	P	4	237-280	VG, 1 vapour phase inclusion
	S	5	124-182	
C12	P(?)	2	205-283	
	S	4	137-173	
C13	P	4	233-264	
	S	5	139-181	
Joon				
J1	P	2	263-268	
	S	4	121-141	
J2	P	3	261-291	VG
	S	5	136-149	
J3	P	5	233-281	One vapour phase inc.
	S	6	131-153	
J4	P	4	212-276	VG
	S	4	131-160	
J5	P	2	239-248	VG
	S	5	137-181	
J6	P	4	244-273	
	S	4	123-131	
J7	P	1	314	One vapour phase inc.
	S	3	122-143	
J8	P	3	261-289	
	S	5	111-139	
J10	P	3	253-281	
	S	4	107-136	
Ruth				
R2	P	3	203-276	
	S	4	160-180	
R3	S	3	178-210	
R4	P	2	283-291	
	S	4	113-138	
R6	P	3	232-245	VG
	S	5	126-161	
R7	P	2	245-322	One vapour phase inc.
	S	4	122-135	
R8	P	3	213-251	
	S	3	131-164	
R9	P	2	244-267	
	S	5	121-182	
R10	P	2	233-250	
	S	4	116-153	

Locality and Sample Number	Inclusion Class	Number Measured	Th°C Range	Remarks
Ptarmigan				
P1	P	3	293-315	
	S	5	108-133	
P3	P	1	243	
	S	4	111-157	
P4	P	4	262-301	One vapour phase inclusion
	S	5	126-186	
P5	P	3	237-288	
	S	5	143-202	
Tom				
T1	P	2	254-296	
	S	6	103-142	
T3	P	4	201-281	
	S	6	117-183	
T4	P	4	263-294	
	S	5	123-214	
Tin				
S1	P	3	281-305	
	S	5	131-193	
S2	P	5	243-322	
	S	6	118-173	
TA				
D1	P	4	221-283	One vapour phase inc.
	S	6	121-175	
D4	P	3	291-331	VG
	S	5	126-162	
D5	P	3	264-294	
	S	6	135-202	
D6	P	2	273-289	VG
	S	5	116-180	
D8	P	3	263-286	
	S	4	121-198	
Hidden Lake				
H1	P	3	225-285	
	S	6	115-165	
H2	P	2	264-271	
	S	4	126-152	
H3	P	1	293	
	S	5	109-151	
H5	S	3	135-147	

Locality and Sample Number	Inclusion Class	Number Measured	Th°C Range	Remarks
H6	P	4	241-311	One vapour phase inclusion
	S	5	118-164	
H7	P	3	264-325	
	S	3	125-146	
H9	S	4	131-180	
H11	P	2	309-314	
	S	6	117-183	

P = primary
S = secondary
Th = temperature of homogenization
VG = visible gold